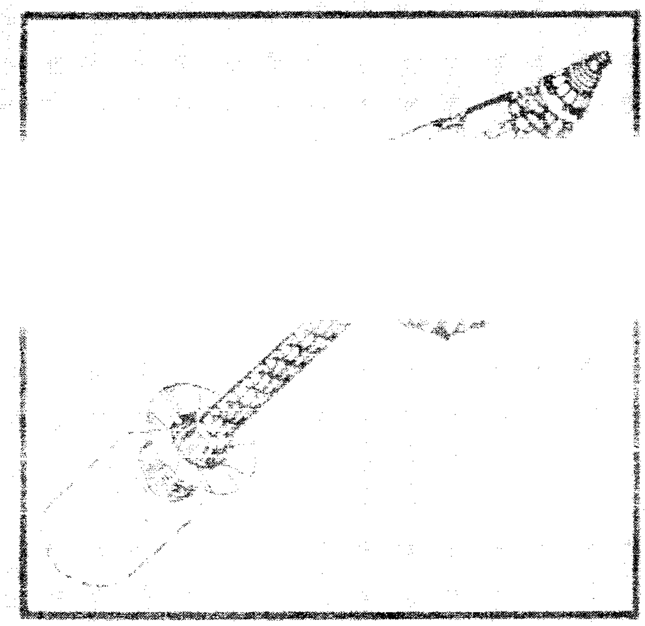
PATHFINDER

JOINT MEETING ON POWER AND PROPULSION TECHNOLOGIES FOR CARGO VEHICLE PROPULSION

NASA HEADQUARTERS
WASHINGTON, D.C.
FEBRUARY 8, 1989



Meeting Proceedings

Office of Aeronautics and Space Technology
National Aeronautics and
Space Administration
Washington, D.C. 20546

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NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

24 March 1989

Reply to Attn of: RP

Distribution

Attached is a summary of the joint meeting held on 8 February 1989 on power and propulsion technologies for the Cargo Vehicle Propulsion element of the Pathfinder program. Representatives from NASA and DOE attended and presented status reports on the Pathfinder program, the Cargo Vehicle Propulsion program element of Pathfinder, NASA-sponsored research on electric propulsion, and space nuclear power programs. The meeting was held in response to the Exploration Mission/Technology Planning Workshop held at NASA Headquarters on 14-17 November 1988 in which closer coupling of power and propulsion on Cargo Vehicle Propulsion was suggested.

I would like to thank the attendees for their fine support of the meeting and for helping initiate this technical dialogue between the power and propulsion communities. If there are questions or if there is a need for additional information please contact the undersigned.

Gary L. Bennett
Manager
Advanced Space Power Systems
Propulsion, Power and Energy Division
Office of Aeronautics and Space Technology

Enclosure: summary

24 March 1989

SUMMARY OF JOINT MEETING ON POWER AND PROPULSION TECHNOLOGIES FOR CARGO VEHICLE PROPULSION

Introduction

This document is a summary of the joint meeting held to discuss power and propulsion technologies for the Pathfinder Cargo Vehicle Propulsion program element. Representatives from NASA and DOE attended and presented status reports on the Pathfinder program, the Cargo Vehicle Propulsion program element of Pathfinder, NASA-sponsored research on electric propulsion, and space nuclear power programs. The meeting was held in response to the Exploration Mission/Technology Planning Workshop held at NASA Headquarters on 14-17 November 1988 in which closer coupling of power and propulsion on Cargo Vehicle Propulsion was suggested. In general the attendees gained a better understanding of the status of the relevant propulsion and power technologies and established points of contact for further information exchanges. Future technical interchange meetings are planned at appropriate times.

The subsequent sections elaborate on the meeting. Attachment 1 is a list of attendees and Attachment 2 contains copies of the visual aids used in the meeting. The agenda for the meeting went as follows

- Overview: Pathfinder Program
- Cargo Vehicle Propulsion Program Plan
- Electric Propulsion Status
- Space Nuclear Power Status

Opening Discussion

Gary L. Bennett of NASA/RP opened the meeting and cited the objective as getting the cargo vehicle propulsion community in direct contact with the space nuclear power community with particular emphasis on learning the status of both technologies and how each might affect the other. He noted the close-out discussion from the Exploration Mission/Technology Planning Workshop held at NASA Headquarters on 14-17 November 1989 in which it was noted that closer coupling was needed between the power and propulsion communities on the Cargo Vehicle Propulsion program. This meeting was in direct response to that observation. Bennett emphasized that this was an information exchange meeting. Given the fact that the Cargo Vehicle Propulsion program element of the Pathfinder Program will not be funded until FY 1991, NASA is not in a position to support power/propulsion system studies.

John W. Warren of DOE/NE gave an overview of the Multimegawatt (MMW) space reactor program, which is jointly sponsored by DOE and SDIO. The goal of MMW is to develop a space reactor for power levels beyond the SP-100 space reactor, encompassing burst modes (tens to hundreds of megawatts of electrical power) and continuous modes (tens of megawatts of electrical power). While MMW is being aimed at SDI applications, Warren said that it could also be used on future civilian missions. He said initially DOE and its contractors had assessed 20 nuclear reactor concepts for use in the MMW program and had narrowed these down to 6 concepts for the Phase I study. Proposals for the Phase II follow-on, which will include up to 3 concepts, are due on 17 February 1989. Following receipt of the proposals there will be a two-month evaluation process with an announcement in April and contracts in July. The ultimate goal is to flight test a reactor in the early 21st century. Current funding levels for both DOE and SDIO are about $9M in FY 1989 and a planned $12M in FY 1990.

There followed some general discussion of facilities, schedules and costs. In response to a question about the type of power MMW could produce (electric propulsion might need 20 kA at 200 to 300 V), representatives from DOE's Idaho National Engineering Laboratory (INEL) said that MMW could be configured to produce whatever combination of voltage and current the user needed.

Overview of the Pathfinder Program

John Mankins, NASA's acting program manager for the Pathfinder Program, gave an overview of the Pathfinder Program which is a new initiative starting in FY 1989. The basic goals include developing the critical technology opportunities for a range of future solar system exploration missions and to support a national decision regarding future missions in the early 1990s. Among the objectives are producing the initial critical research results and validating the key capabilities by the early 1990s and achieving the necessary levels of readiness and to transition the technologies to mission users beginning in the mid 1990s.

Mankins noted that Pathfinder is organized into four major program areas: (1) Surface Exploration; (2) In-Space Operations; (3)

Humans-in-Space; and (4) Space Transfer plus mission studies. These four major program areas are further subdivided into 20 element programs. The programs are managed through the NASA centers. Cargo Vehicle Propulsion is one of the 20 element programs and it falls under the Space Transfer program area.

Mankins noted that a cumulative budget of about $840M was originally estimated to be needed to support the proposed early 1990s decision. Of this $100M was to be provided in Fy 1989; however, only $40M was provided. In FY 1990, the request was for $140M but to date the indications are that only $47M will be provided. Given this situation it is obvious that the originally projected milestones cannot be met. One of the program elements affected by these cuts is Cargo Vehicle Propulsion which will not be funded until FY 1991.

Jimmy M. Underwood, Director of Technology in NASA's Office of Exploration, requested a top level listing of missions and power requirements. He emphasized the need to develop an easily deployable reactor for surface power.

Summary of the Pathfinder Cargo Vehicle Propulsion Program Plan

James R. Stone, who is on assignment at NASA HQ from NASA/LeRC and is the Cargo Vehicle Propulsion program manager, summarized the program plan for Cargo Vehicle Propulsion. He provided background information on the need for electric propulsion with specific impulses over 39,000 m/s (>4,000 lbf-s/lbm) in order to provide the propellant mass savings needed to realize future missions such as manned exploration of Mars. Electric propulsion for a Mars mission would require about 1 to 5 MWe if the mission were flown from low Lunar orbit (LLO) but about 1000 MWe if the mission were flown from low Earth orbit (LEO). Even the relatively less demanding missions to lunar orbit would require about from 0.5 to 1 MWe from LEO. Thus, there is a a need for large amounts of power for spacecraft using electric propulsion

Stone reviewed the two principal types of electric propulsion systems under consideration for Cargo Vehicle Propulsion: ion thrusters and magnetoplasmadynamic (MPD) thrusters. Within MPD are self-field MPD thrusters and applied-field MPD thrusters. The program encompasses the thruster research, facilities, thermal analyses, power processors and systems definitions. The program does not include power, which is assumed to be provided by one of the other national programs. He said the program goals for Cargo Vehicle Propulsion included establishing the feasibility of electric thrusters for major Mars and lunar missions; establishing the feasibility of 10^8 N-s total impulse; and selecting the most promising of the two types for further development. The program is laid out in three phases, the last one leading to a flight validation in the early 21st century.

Stone described the management structure for Cargo Vehicle Propulsion. The program manager resides in the Propulsion, Power and Energy Division of NASA HQ and the project office (lead center) is at LeRC. Both LeRC and JPL are participating centers. The schedule and currently planned funding profile were described.

In response to a question, David Q. King of JPL stated that the specific mass for an MPD thruster was about 1 kg/kW and that it required a voltage on the order of 10 to 20 kV AC. The issue of scalability of electric propulsion was discussed.

There was some discussion on the need for close interaction between the Office of Exploration (Code Z) and the Office of Aeronautics and Space Technology (Code R) in establishing mission requirements and knowing the technology implications of the various mission options. It was generally agreed that an integrated plan was needed on how the mission options and technologies come together.

Regarding the power/propulsion interface, David C. Byers of LeRC noted that, based on his experience with previous electric propulsion tests, the interface is "pretty clean", i.e., the interface can be treated through specifications. Byers noted that the power processor specific mass might be on the order of 3 kg/kW. He noted the concern over reactor operating temperatures and said the electric propulsion system cannot operate at reactor radiator temperatures; instead, it must operate at temperatures more typical of those of electronic components.

Electric Propulsion Technology Status

James S. Sovey of LeRC provided a background briefing on electric propulsion and then discussed the technology status of ion engines. David Q. King of JPL reviewed the technology status of MPD thrusters and provided a summary of electric propulsion.

Sovey began by noting that electric propulsion provides a number of mission benefits including reduced mass to LEO. For a Mars cargo vehicle he said the requirements were a specific mass of <10 kg/kW at power levels on the order of 4 to 10 MWe with a specific impulse of 49,000 m/s (5,000 lbf-s/lbm). To minimize the mass in LEO and the trip time he said the efficiencies would have to be >0.60 for MPD and >0.75 for ion thrusters. The desired total impulse per thruster is 1×10^8 to 5×10^8 N-s.

Sovey described the demonstrated performance in electric propulsion and noted that the key technical issues were scaling in ion thrusters and improving MPD thruster performance. Currently the demonstrated thruster power is one to two orders of magnitude below the desired MW levels needed for a cargo vehicle while the demonstrated total impulse is about two orders of magnitude below the desired MW levels.

Sovey reviewed the reasons for selecting ion thrusters and MPD thrusters for cargo vehicle propulsion. The former provides high efficiency and high specific impulse while the latter provides both high power and thrust density and high specific impulse.

Sovey then reviewed the two basic ion thruster designs -- divergent field and ring cusp -- and then presented experimental data and analyses to show the technological maturity of ion propulsion. A key issue that was highlighted throughout the meeting was the need for large vacuum facilities with high pumping speeds in order to conduct meaningful tests of ground-based electric propulsion systems.

Sovey concluded by noting that scaling is the key technology issue facing ion thrusters. He emphasized the need for better communication at the system level.

David Q. King of JPL began his MPD review by describing foreign activities relating to electric propulsion. Active programs are under way in Japan, Federal Republic of Germany (FRG), the United Kingdom (U.K.), Italy, People's Republic of China (PRC), and the USSR. He noted that FRG has the longest reported exposure with MPD.

King noted that in working on NASA's electric propulsion program, JPL has tended to deal with the issues affecting lifetime and LeRC has tended to focus on issues affecting performance. King described the liquid-cooled, applied field, hybrid MPD, which JPL has just begun to examine. He also reviewed the basics of MPD operation and the thruster operational runs made at JPL. King described the two operating modes which have been observed at JPL and the current MPD research program at JPL.

King noted the need to keep the power ripple <1% for frequencies below 500 Hz. (A similar rule-of-thumb has been learned by the light bulb industry.) He said ripple in the power processor may determine the lifetime of the cathode. He noted that 10 to 20% of the input power is rejected by the anode and asked whether the heat from the MPD could be sent back into the power cooling system. The space reactor people agreed to consider that option.

Byers emphasized the need to work the issue of the temperature of the heat rejection system.

Plume effects, both thermal and electrical, are important interface issues. For example, it was also noted that there will be 20 - 30 kA of electrons and an equal number of ions coming out of the MPD. The system must be allowed to equilibrate so that there is not a lot of return flux.

King closed by noting that in Europe and Japan there is significant competition for SP-100 propulsion and planetary exploration and that the USSR has operational electric propulsion systems. Like Sovey, King noted the issue of scaling to the power levels needed for cargo vehicles and the need for adequate facilities for testing.

Space Nuclear Power Status

Jack F. Mondt of JPL and Deputy Manager of the SP-100 Project provided a technology status on the SP-100 space reactor program, which is jointly funded by NASA, DOE and DoD. He said the goal of the program is to provide electric power (from about 10 kWe to about 1,000 kWe) for a variety of space missions and SP-100 is currently in the ground engineering system (GES) phase which is designed to demonstrate that the technology is ready for flight application. Under the GES program the power system hardware will be designed, built and ground-tested for lifetime and performance.

Mondt described the overall power system and noted the results of a recent mass minimization study showed that for a specific mission, the mass of SP-100 could be 3,615 kg. He showed various system configurations that could be used depending upon the mission and he described the characteristics and performance parameters of each.

Mondt reviewed the SP-100 fuel pin irradiation program and the power conversion system work, providing detailed insights into the thermoelectric program and the power conditioning, control and distribution (PCC&D) subsystem. He said SP-100 provides DC power at 200 V. He said there were 12 power converter subsystems (PCSS) that will provide about 9 kWe each. The integrated assembly test (IAT) of SP-100 is scheduled for FY 1994 although recent funding changes could impact this.

Marland L. Stanley of INEL and Project Manager of the Multimegawatt (MMW) Space Reactor Project provided an overview on that program. The MMW program is basically driven by requirements from the Strategic Defense Initiative Organization (SDIO) to provide safe, reliable, cost-effective electrical power in the multimegawatt range for use by space weapons and surveillance platforms. He said the objective is to identify and develop at least one space nuclear system concept by the mid 1990s.

Stanley said the MMW strategy has been to follow a phased concept down-selection. They began with 20 preliminary system concepts and are now working on a downselection to possibly 3 concepts, hopefully covering burst power capabilities (from tens to hundreds of megawatts) and continuous power (in the range of tens of megawatts). Some of the concepts can involve effluents. The various categories of MMW concepts were described along with the technical issues that must be resolved. The resolution of these issues along with safety, reliability, mass/volume, operations, development risk, and life cycle cost are part of the evaluation process for downselection. Specific masses in the range from about 1 kg/kWe to about 8 kg/kWe were shown.

Stanley said they will announce their selections in April and that they plan to be under contract in July. He said it would be helpful to the MMW program to know what the electric propulsion thrust requirements are (e.g., how long are the thrust periods, how many are there, etc.) and whether or not an open cycle conversion system would be acceptable. In general it was believed that for Cargo Vehicle Propulsion, a closed cycle would be preferred.

There was a brief discussion about the flexibility of the MMW concepts and their adaptability to other applications such as bimodal and direct nuclear thermal rocket propulsion.

Wrap-up/Summary

Gary Bennett summarized the meeting by noting

- Both Cargo Vehicle Propulsion and the space nuclear power program appear to be on compatible schedules with each other but, given the funding constraints, not necessarily with some of the proposed missions that would need these two technologies.

- Based on a first look by the two communities of experts it appears possible to have a clean interface between electric propulsion and power provided that consideration is given to

  - ripple in the power
  - plumes/fields/particles
  - operating and rejection temperatures

There was general agreement by the attendees that there should be future technical interchange meetings. The INEL representatives suggested that perhaps a June meeting would be in order because then the results of the MMW downselection would be known. The NASA representatives asked DOE for copies of the MMW executive summary.

NASA

OAST

PROPULSION, POWER & ENERGY

JOINT MEETING ON POWER & PROPULSION TECHNOLOGIES FOR CARGO VEHICLE PROPULSION

8 FEBRUARY 1989

NASA HEADQUARTERS

NASA

OAST

PROPULSION, POWER & ENERGY

JOINT MEETING ON
POWER AND PROPULSION TECHNOLOGIES
FOR
CARGO VEHICLE PROPULSION

OBJECTIVE

TO GET THE CARGO VEHICLE PROPULSION COMMUNITY IN DIRECT CONTACT WITH THE SPACE NUCLEAR POWER COMMUNITY WITH PARTICULAR EMPHASIS ON LEARNING THE STATUS OF BOTH TECHNOLOGIES AND HOW EACH MIGHT AFFECT THE OTHER

Office of
Aeronautics and
Space
Technology

PATHFINDER

PROGRAM OVERVIEW

Presentation to

**JOINT DOE-NASA MEETING ON
POWER AND PROPULSION TECHNOLOGIES
FOR NUCLEAR ELECTRIC PROPULSION**

John C. Mankins
Pathfinder Program
Manager (Acting)
February 8, 1989

PATHFINDER
PROGRAM OVERVIEW

OAST

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JCM-0744

PATHFINDER
GOALS & OBJECTIVES

O-A-S-T

GOALS

- Develop Critical Technology Opportunities For A Range Of Future Solar System Exploration Missions
- Support A National Decision Regarding Future Missions In The Early 1990s Timeframe
- Support Broad U.S. Civil Space Technology Leadership

OBJECTIVES

- Produce Initial Critical Research Results And Validate Key Capabilities By The Early 1990s
- Achieve Necessary Levels of Readiness And Transition Technologies To Mission Users Beginning In The Mid-1990s
- Define And Achieve The Right Balance Between More Basic Research And Focused Demonstrations
- Coordinate R&T With Other NASA Offices And Support On-Going NASA Mission Studies
- Build A Partnership Between NASA, Industry & Universities

JCM-0243

PATHFINDER
ORGANIZATION AND MANAGEMENT

O-A-S-T

ORGANIZATION

- FOUR MAJOR PROGRAM AREAS, PLUS MISSION STUDIES
- EIGHTEEN ELEMENT PROGRAMS

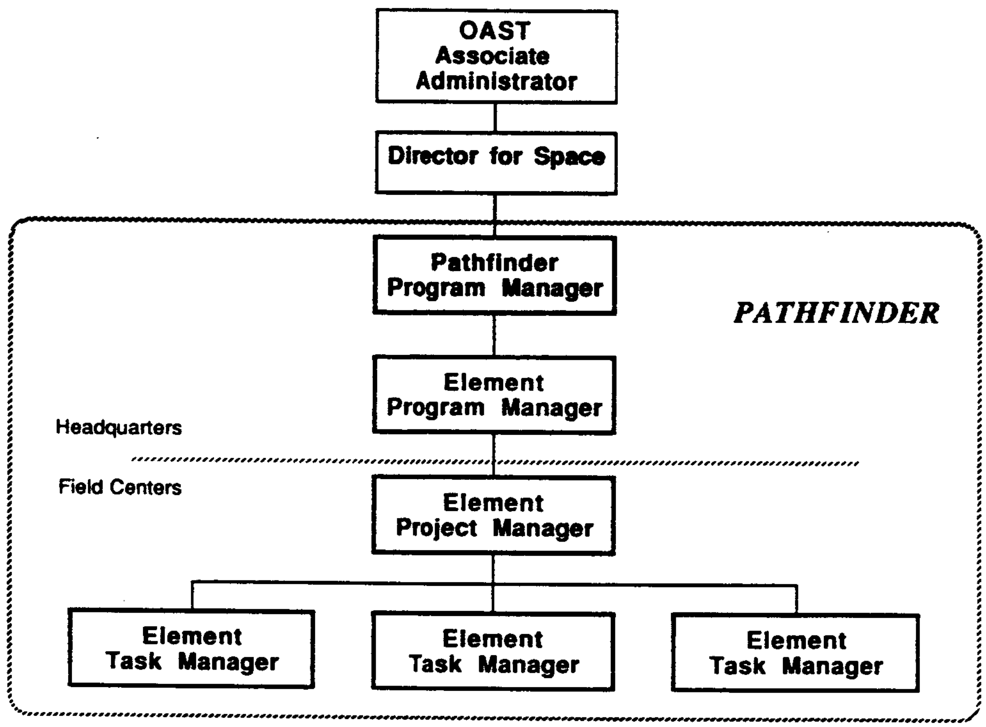
MANAGEMENT

- COHESIVE MANAGEMENT STRUCTURE
- LEAD FIELD CENTERS FOR MOST ELEMENTS
- RESEARCH AND TECHNOLOGY IN A "PROJECT-STYLE" OF MANAGEMENT

JCM-0757

PATHFINDER
MANAGEMENT APPROACH

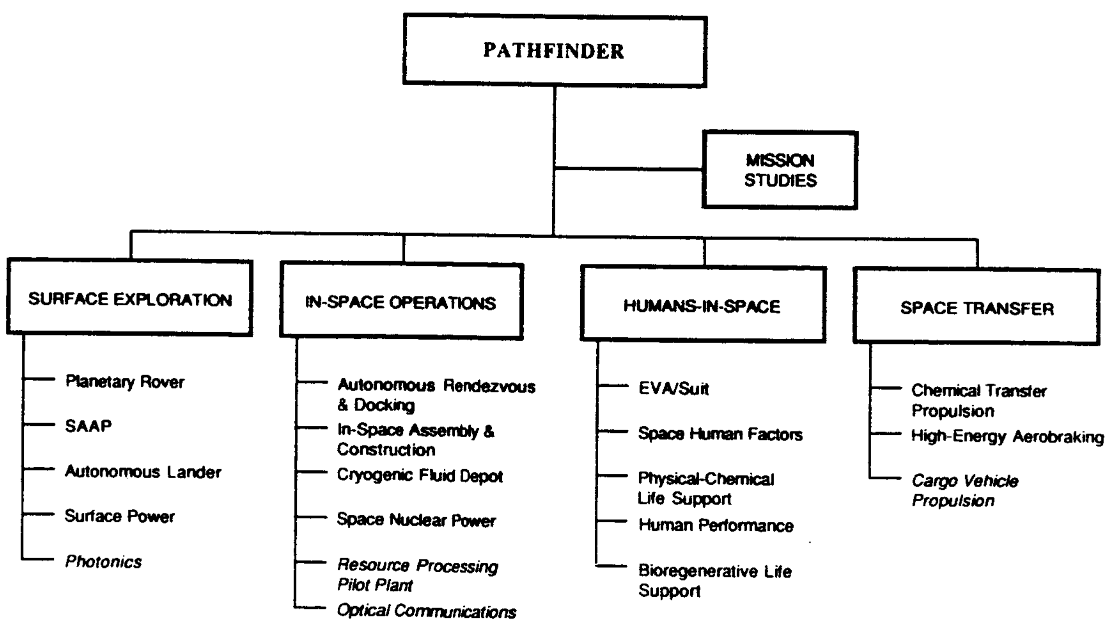
O-A-S-T



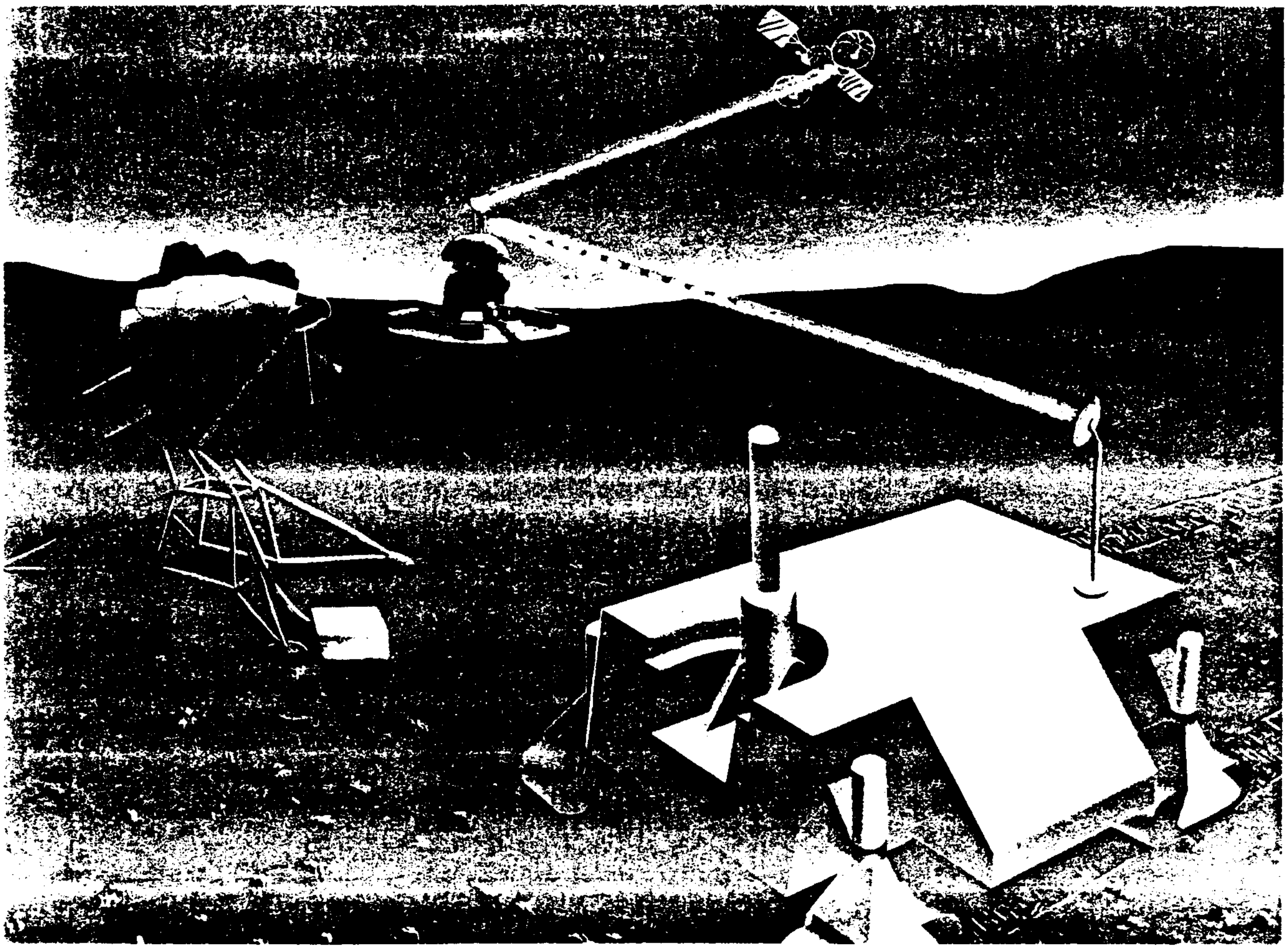
JCM-0737

PATHFINDER
WORK BREAKDOWN STRUCTURE

O-A-S-T



JCM-0756



PATHFINDER PROGRAM AREA
SURFACE EXPLORATION

OAST

TECHNOLOGY NEEDS

- PILOTED AND AUTOMATED SURFACE MOBILITY AND MANIPULATION SYSTEMS
- MOBILE AND STATIONARY SURFACE POWER SYSTEMS (SOURCES AND STORAGE)
- ADVANCED SPACE COMPUTING, WITH GROUND & ON-BOARD AUTONOMOUS SYSTEMS
- MULTIPLE SENSORS (REMOTE AND LOCAL)
- SURFACE MATERIALS, STRUCTURES, AND MECHANISMS
- TECHNOLOGIES FOR SURFACE SCIENCES (E.G., SAMPLING AND IN SITU ANALYSIS)

JCM-0750

PATHFINDER PROGRAM AREA
SURFACE EXPLORATION

O-A-S-T

ELEMENT PROGRAMS

- PLANETARY ROVER
- SAMPLE ACQUISITION, ANALYSIS, & PRESERVATION
- AUTONOMOUS LANDER
- SURFACE POWER
- PHOTONICS

JCM-0745

PATHFINDER PLANETARY ROVER

OAST

TECHNOLOGIES
• MOBILITY • AUTONOMOUS GUIDANCE • SAMPLING ROBOTICS • ROVER POWER

MISSION APPLICATIONS
• LUNAR ROVERS (Piloted & Robotic) • MARS ROVERS (Piloted & Robotic) • OTHER ROBOTIC EXPLORATION AND SAMPLE RETURN MISSIONS (e.g., CNSR)

JCM-0053

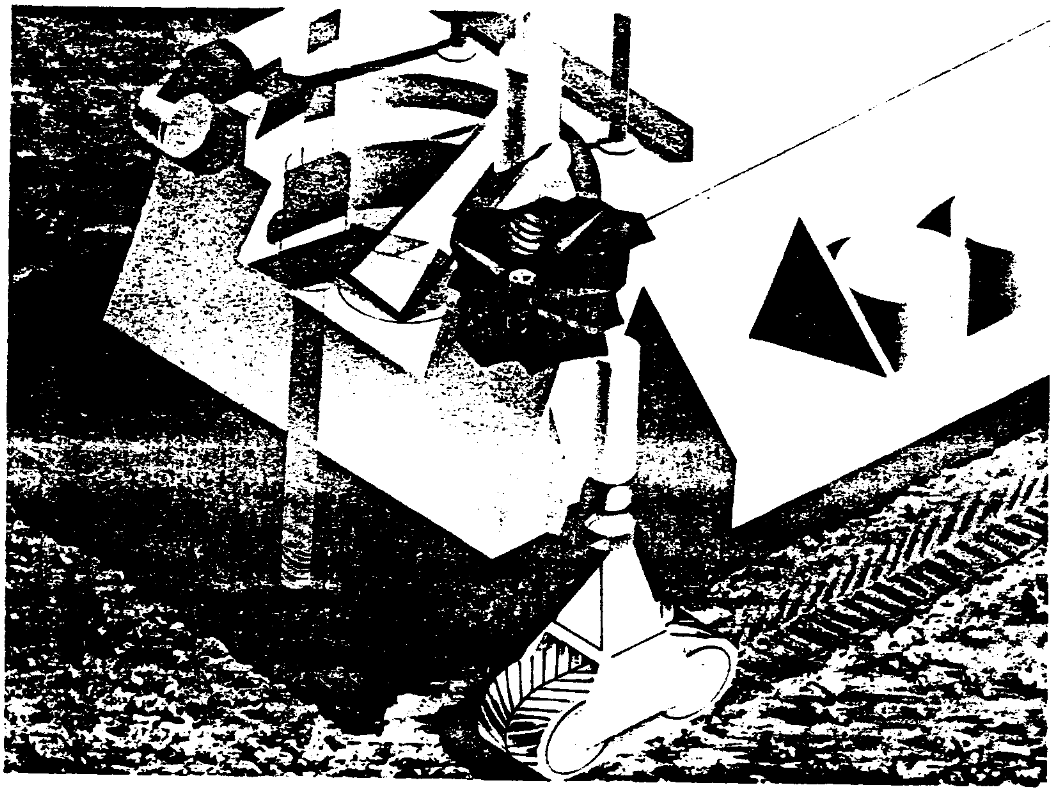
PATHFINDER PLANETARY ROVER

OAST

PROGRAM MANAGEMENT

- LEAD OAST DIVISION:
  Information Sciences And Human Factors Division
- LEAD NASA FIELD CENTER:
  Jet Propulsion Laboratory
- PARTICIPATING CENTERS:
  Ames Research Center
  Langley Research Center
  Lewis Research Center
- FY 1989 BUDGET: $ 5 MILLION

JCM-0758



PATHFINDER
SAMPLE ACQUISITION, ANALYSIS & PRESERVATION

OAST

TECHNOLOGIES
• SAMPLING TOOLS & SYSTEMS • CHEMICAL/PHYSICAL ANALYSIS SENSORS • PRESERVATION (e.g., Materials, Seals)

MISSION APPLICATIONS
• LUNAR ROVERS (Piloted & Robotic) • MARS ROVERS (Piloted & Robotic) • OTHER SAMPLE RETURN MISSIONS (CNSR)

JCM-0054

PROGRAM MANAGEMENT

- **LEAD OAST DIVISION:**
  Materials and Structures Division

- **LEAD NASA FIELD CENTER:**
  Jet Propulsion Laboratory

- **PARTICIPATING CENTERS:**
  Ames Research Center
  Johnson Space Center

- **FY 1989 BUDGET: $ 1 MILLION**

JCM-0759

PATHFINDER
AUTONOMOUS LANDER

OAST

TECHNOLOGIES

- GN&C (Terminal Descent)
- SENSORS
- SYSTEMS AUTONOMY
- MECHANIZATION/MECHANICAL SYSTEMS

MISSION APPLICATIONS

- LUNAR OUTPOST OPERATIONS VEHICLES
- ROBOTIC SOLAR SYSTEM EXPLORATION
- PILOTED MARS EXPEDITION

JCM-0069

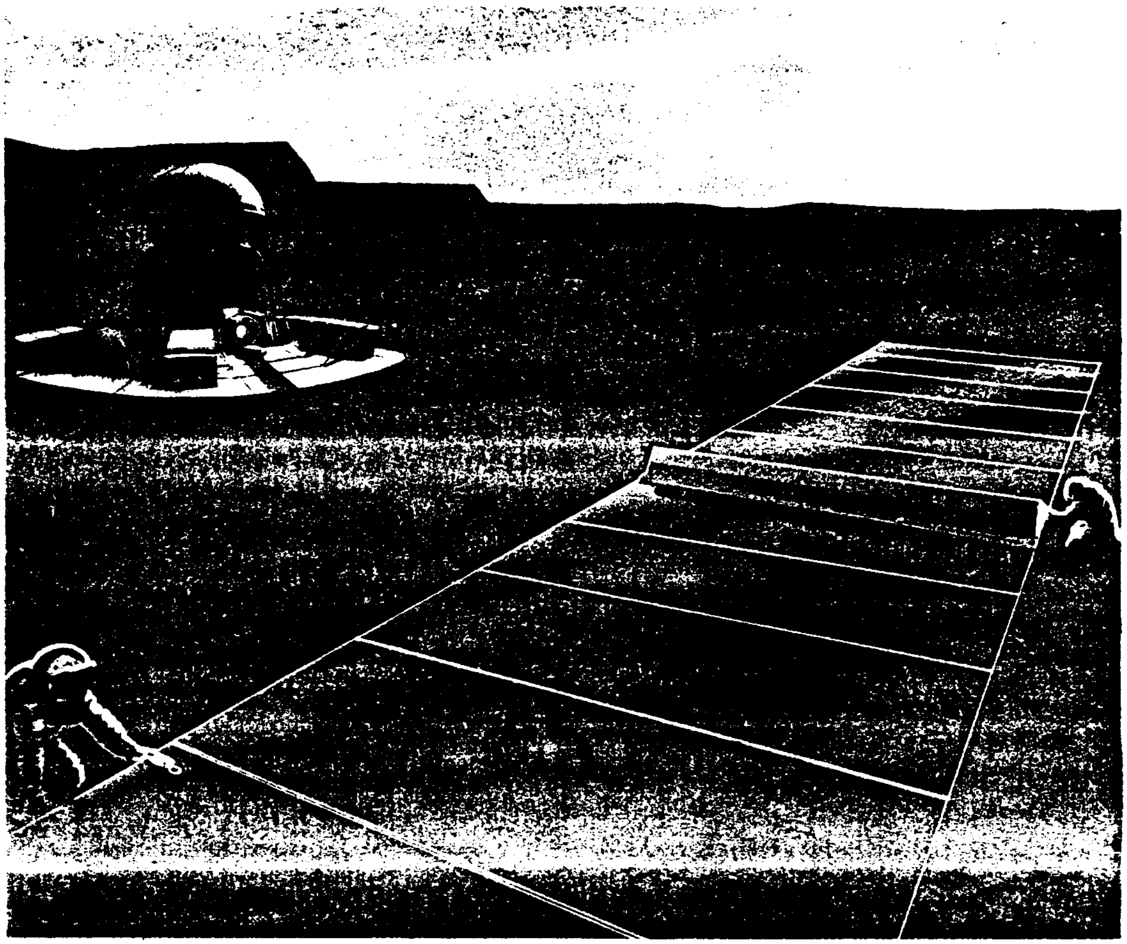
PATHFINDER
AUTONOMOUS LANDER

OAST

PROGRAM MANAGEMENT

- LEAD OAST DIVISION:
  Information Sciences & Human Factors Division
- LEAD NASA FIELD CENTER:
  Johnson Space Center
- PARTICIPATING CENTERS:
  Ames Research Center
  Jet Propulsion Laboratory
- FY 1989 BUDGET: $ 1 MILLION

JCM-0760



PATHFINDER SURFACE POWER

O-A-S-T

TECHNOLOGIES
• ADVANCED PHOTOVOLTAICS • POWER STORAGE (e.g, Fuel Cells) • ENVIRONMENTAL COUNTERMEASURES

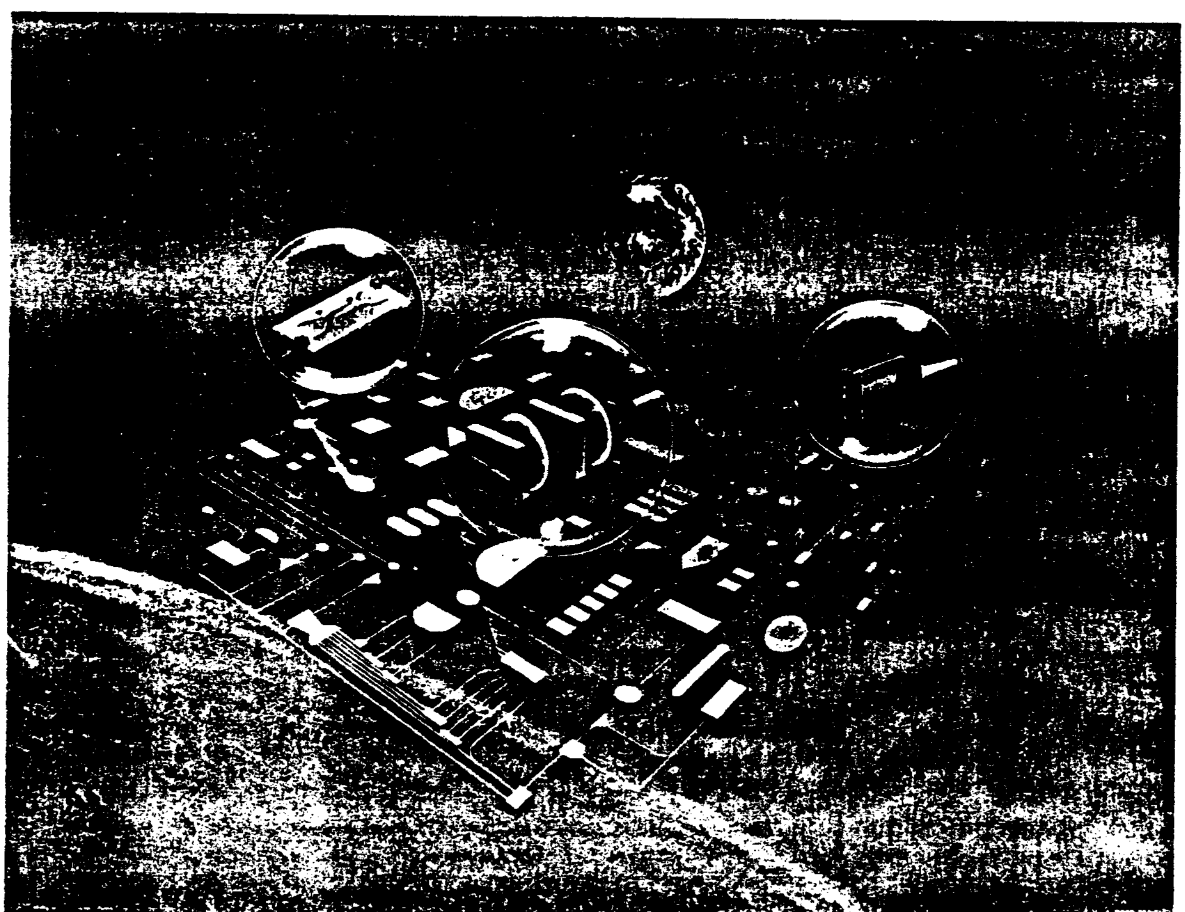
MISSION APPLICATIONS
• LUNAR OUTPOST START-UP • PILOTED MARS EXPEDITIONS • OTHER SPACECRAFT (Earth-orbit, Transfer)

JCM-0055

PROGRAM MANAGEMENT

- **LEAD OAST DIVISION:**
  Propulsion, Power, and Energy Division
- **LEAD NASA FIELD CENTER:**
  Lewis Research Center
- **PARTICIPATING CENTERS:**
  Jet Propulsion Laboratory (Not funded in FY'89)
- **FY 1989 BUDGET: $1.5 MILLION**

JCM-0761



PATHFINDER PHOTONICS

TECHNOLOGIES
• FAULT-TOLERANT ELECTRONICS/ PHOTONICS SYSTEM ARCHITECTURES • PHOTONICS COMPONENTS (Sensors, Memories, Input/Output Components, Image Processing)

MISSION APPLICATIONS
• LUNAR OUTPOST SYSTEMS (e.g., Observatories) • PILOTED PHOBOS/MARS EXPEDITIONS • ROBOTIC SOLAR SYSTEM EXPLORATION (e.g., Autonomous Landers, Planetary Rovers) • ADVANCED EARTH-ORBITING OPERATIONS

JCM-0754

PATHFINDER PHOTONICS

OAST

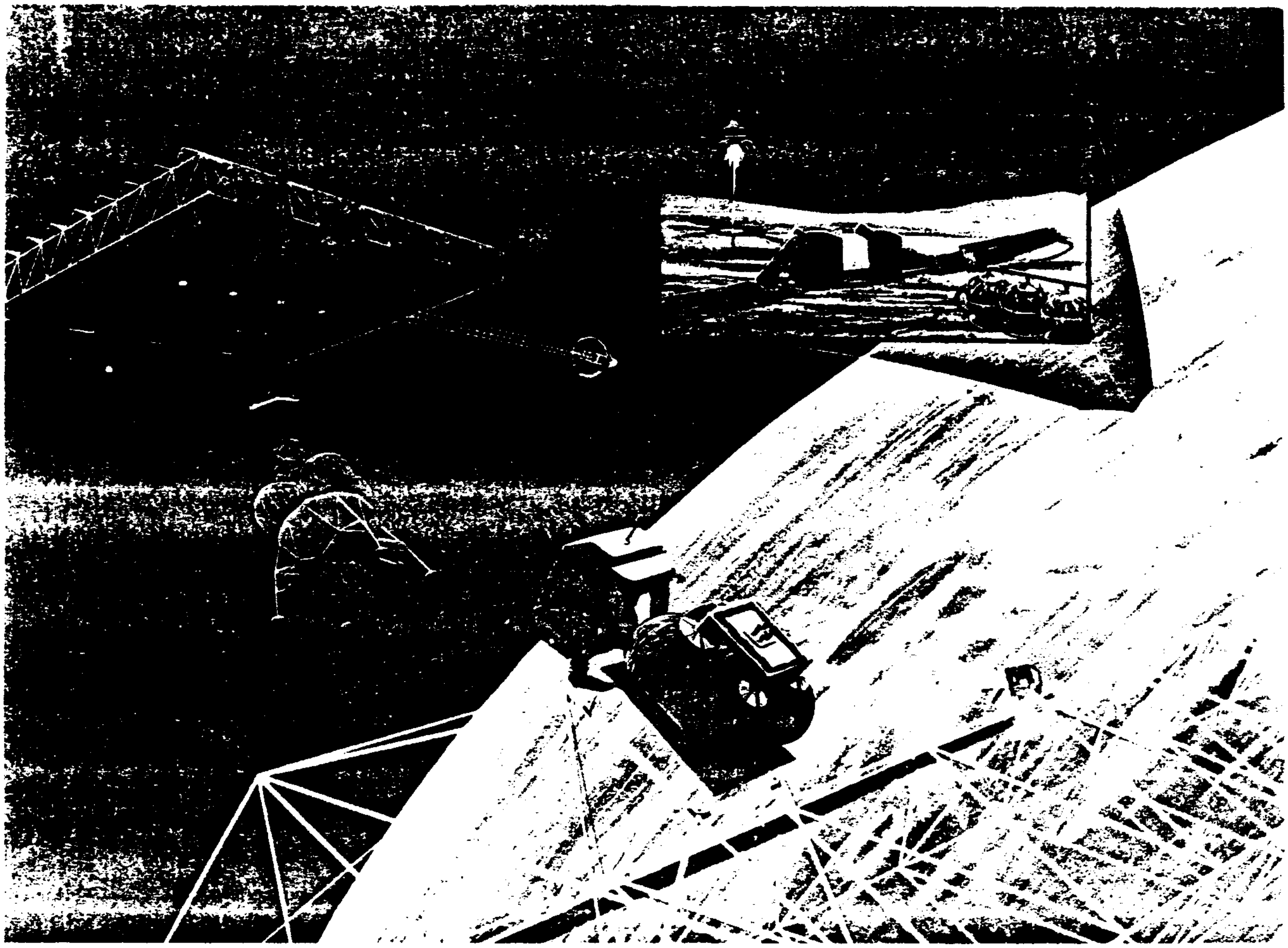
PROGRAM MANAGEMENT

- **LEAD OAST DIVISION:**
  Information Sciences & Human Factors Division

- **PARTICIPATING CENTERS:**
  Ames Research Center
  Jet Propulsion Laboratory
  Johnson Space Center
  Langley Research Center

- **INITIATION DEFERRED TO 1990**

JCM-0762



PATHFINDER PROGRAM AREA
IN-SPACE OPERATIONS

OAST

TECHNOLOGY NEEDS

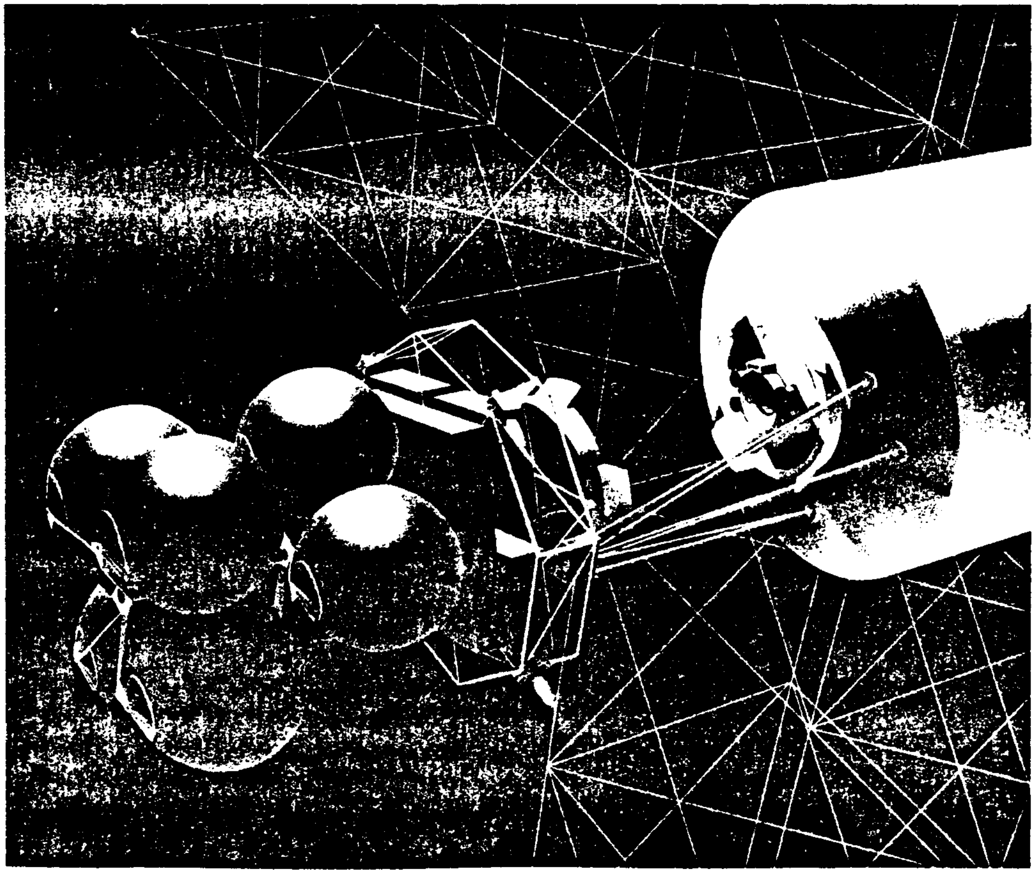
- AUTOMATED AND SEMI-AUTONOMOUS OPERATIONS (E.G., RENDEZVOUS & DOCKING)
- ASSEMBLY, CONSTRUCTION, AND TESTING OF LARGE SPACE SYSTEMS (IN ORBIT AND ON SURFACES)
- MANAGEMENT AND LONG-TERM STORAGE OF CRYOGENIC FLUIDS
- HIGH-CAPACITY POWER SYSTEMS (E.G., NUCLEAR)
- HIGH-RATE SPACE COMMUNICATIONS SYSTEMS
- IN SITU RESOURCE UTILIZATION TECHNIQUES AND HARDWARE (E.G., FUEL PRODUCTION AND MINING)

JCM-0751

ELEMENT PROGRAMS

- AUTONOMOUS RENDEZVOUS & DOCKING
- IN-SPACE ASSEMBLY AND CONSTRUCTION
- CRYOGENIC FLUID DEPOT
- SPACE NUCLEAR POWER (SP-100)
- RESOURCE PROCESSING PILOT PLANT
- OPTICAL COMMUNICATIONS

JCM-0746



PATHFINDER
AUTONOMOUS RENDEZVOUS & DOCKING

OAST

TECHNOLOGIES

- SENSORS (e.g., Laser Ranging, Radars)
- GN&C (Fault-Tolerant, On-Board)
- SYSTEM AUTONOMY

MISSION APPLICATIONS

- SPACE TRANSFER VEHICLES (Earth & Lunar)
- PILOTED MARS EXPEDITION
- ROBOTIC SAMPLE RETURN MISSIONS (MRSR)

JCM-0057

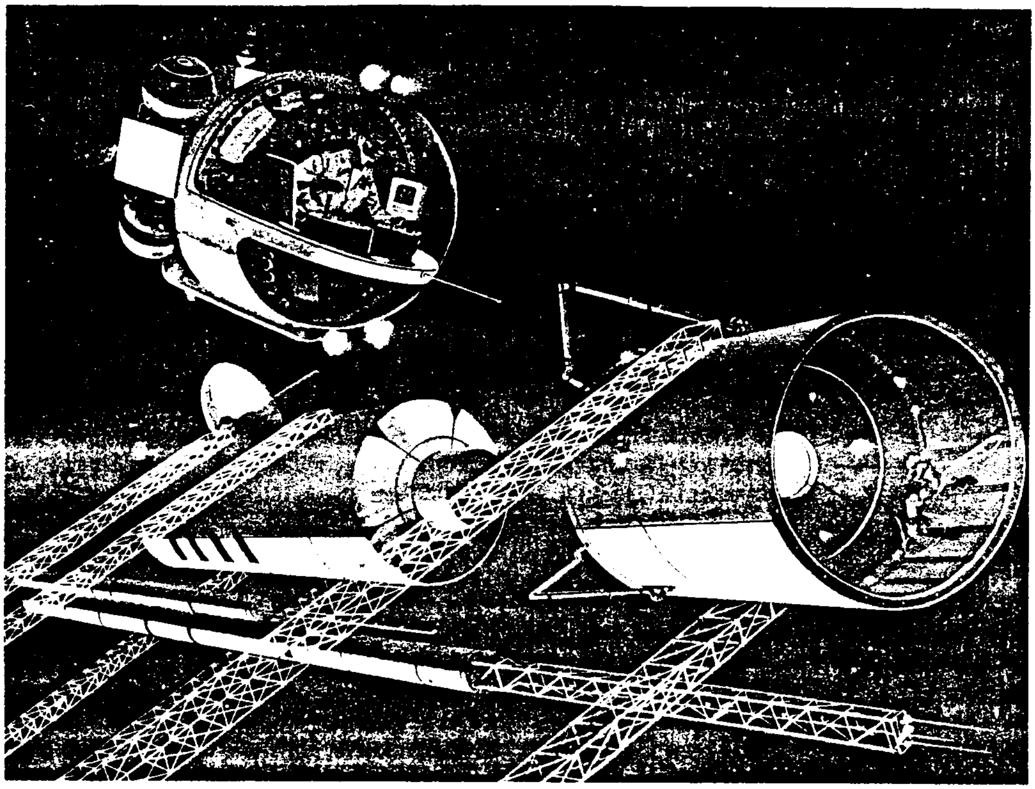
PATHFINDER
AUTONOMOUS RENDEZVOUS & DOCKING

OAST

PROGRAM MANAGEMENT

- LEAD OAST DIVISION:
  Information Sciences & Human Factors Division
- LEAD NASA FIELD CENTER:
  Johnson Space Center
- PARTICIPATING CENTERS:
  Jet Propulsion Laboratory
  Marshall Space Flight Center
- FY 1989 BUDGET: $1 MILLION

JCM-0763



PATHFINDER
IN-SPACE ASSEMBLY AND CONSTRUCTION

OAST

TECHNOLOGIES

- LARGE-SCALE MANIPULATION SYSTEMS (Including highly flexible manipulators)
- JOINING TECHNIQUES (e.g., Welding)
- PRECISION STRUCTURE ALIGNMENT/ADJUSTMENT

MISSION APPLICATIONS

- LUNAR OUTPOST STAGING
- MARS MISSION STAGING (Robotic, Piloted)
- ADVANCED SPACE STATION OPERATIONS
- EARTH-ORBIT OBSERVATORY STAGING

JCM-0059

PROGRAM MANAGEMENT

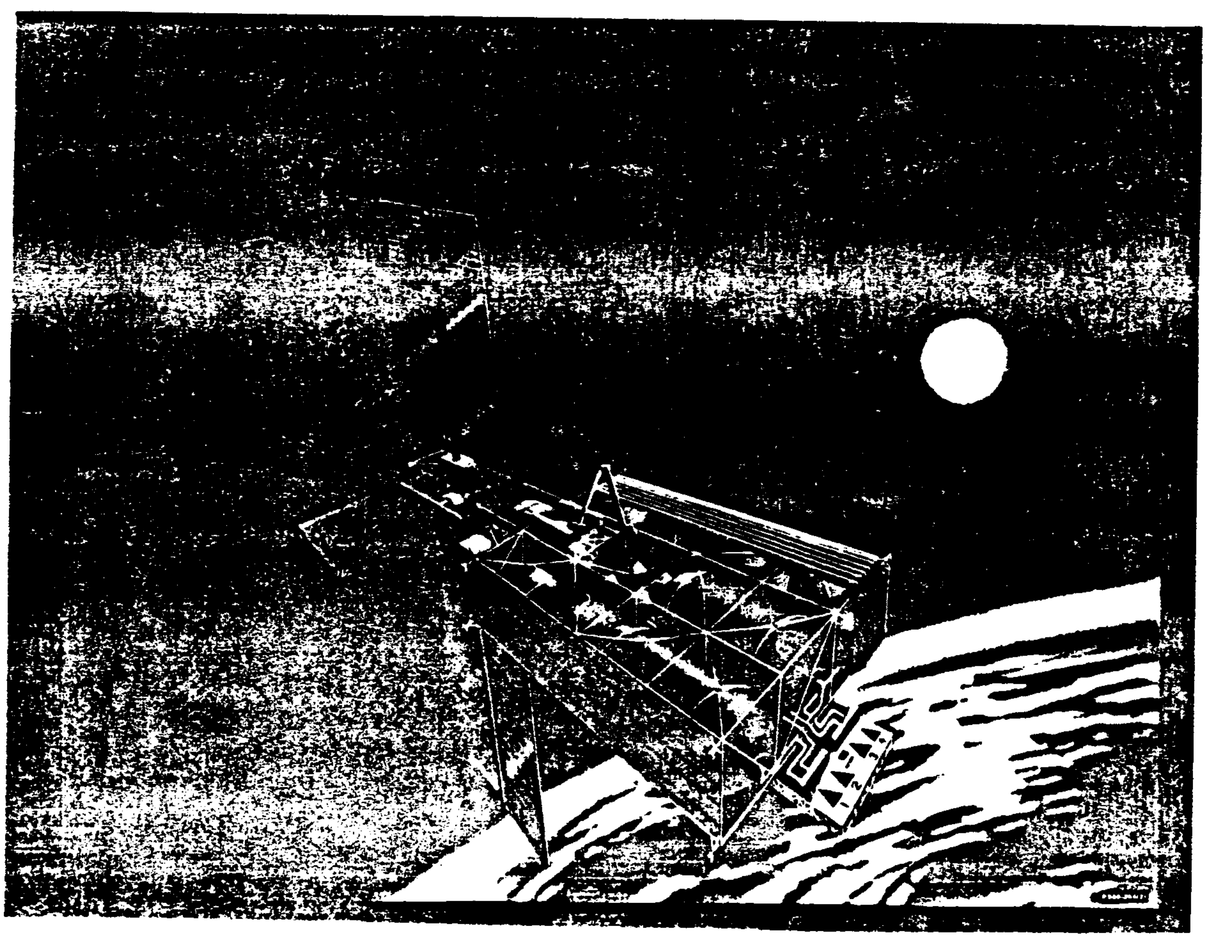
- **LEAD OAST DIVISION:**
  Materials and Structures Division

- **LEAD NASA FIELD CENTER:**
  Langley Research Center

- **PARTICIPATING CENTERS:**
  Jet Propulsion Laboratory
  Johnson Space Center
  Marshall Space Flight Center

- **FY 1989 BUDGET: $1 MILLION**

JCM-0764



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PATHFINDER
CRYOGENIC FLUID DEPOT

TECHNOLOGIES

- LONG-TERM CRYOGEN CONTAINMENT & MANAGEMENT
- REFRIGERATION COMPONENTS/SYSTEMS
- FLUID TRANSFER COMPONENTS/SYSTEMS

MISSION APPLICATIONS

- LUNAR OUTPOST STAGING/OPERATIONS
- MARS MISSION STAGING (Robotic, Piloted)
- ADVANCED SPACE STATION OPERATIONS
- ASTROPHYSCIS OBSERVATORY SERVICING

JCM-0060

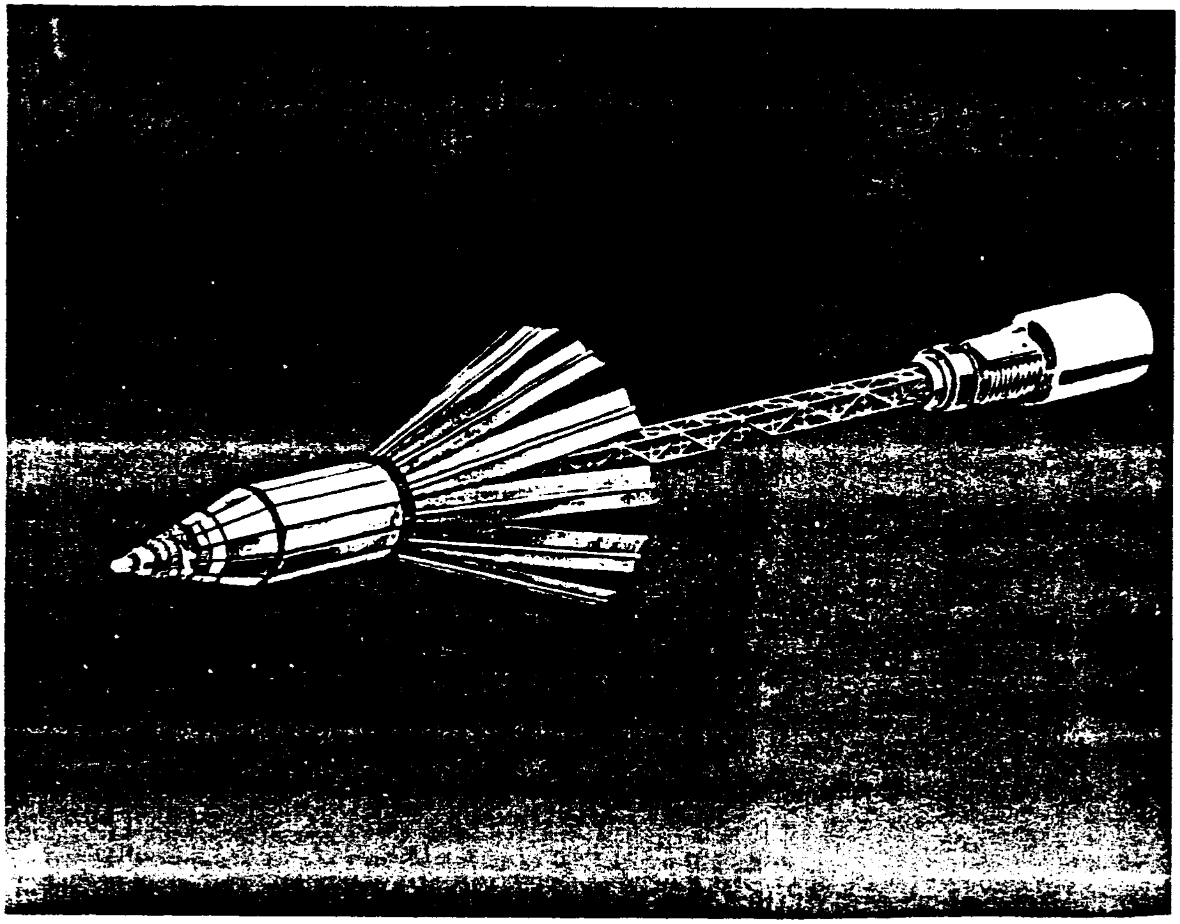
OAST

PATHFINDER
CRYOGENIC FLUID DEPOT

PROGRAM MANAGEMENT

- LEAD OAST DIVISION:
  Propulsion, Power, and Energy Division
- LEAD NASA FIELD CENTER:
  Lewis Research Center
- PARTICIPATING CENTERS:
  Johnson Space Center
  Marshall Space Flight Center
- FY 1989 BUDGET: $3 MILLION

JCM-0765



PATHFINDER
SPACE NUCLEAR POWER (SP-100)

OAST

TECHNOLOGIES

- REFRACTORY METAL REACTOR
- FUEL PINS
- HIGH-TEMPERATURE CONTROL SYSTEM
- LIQUID-METAL THERMOELECTRIC MAGNETIC PUMP
- THERMAL-TO-ELECTRIC CONVERSION
- HEAT-PIPE HEAT-REJECTION SYSTEMS

MISSION APPLICATIONS

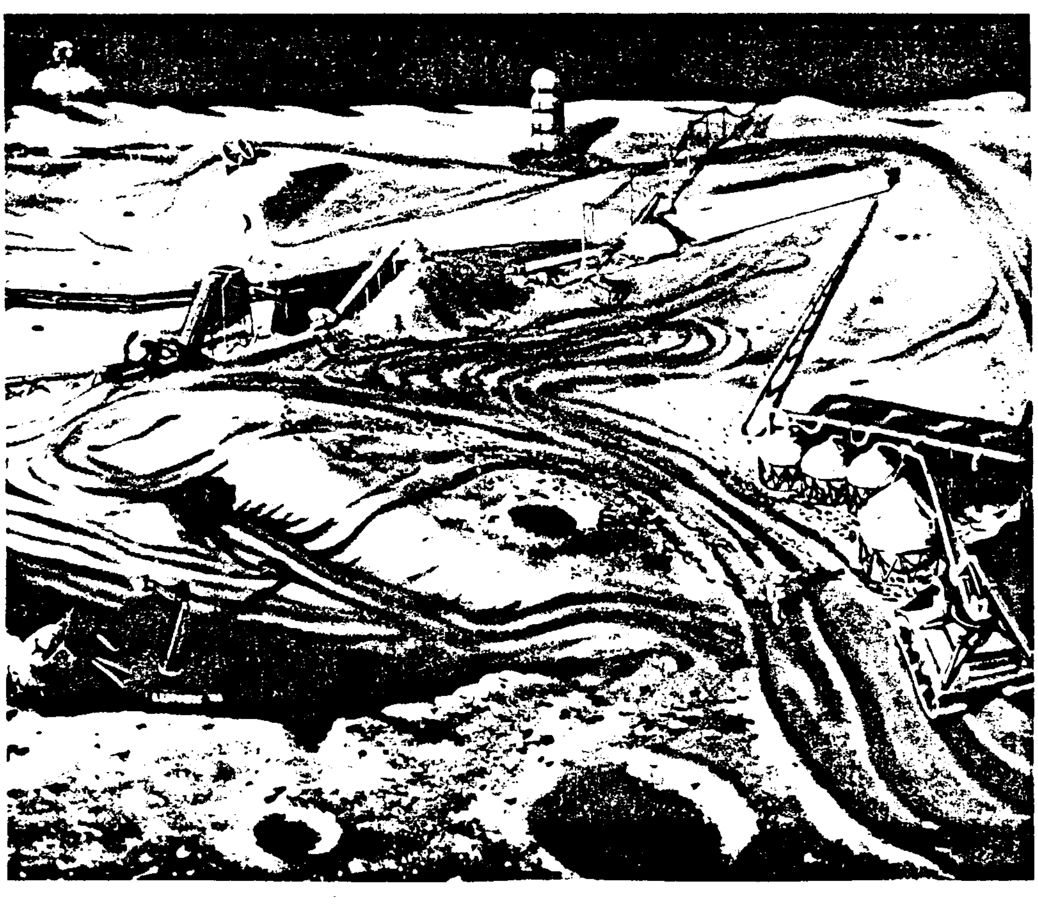
- LUNAR/MARS OUTPOSTS
- PILOTED MARS EXPEDITION
- ADVANCED EARTH-ORBIT OPERATIONS
- ROBOTIC SOLAR SYSTEM EXPLORATION (Nuclear Electric Propulsion/Power)

JCM-0061

PROGRAM MANAGEMENT

- **LEAD OAST DIVISION:**
  Propulsion, Power, and Energy Division
- **LEAD NASA FIELD CENTER:**
  Jet Propulsion Laboratory
- **PARTICIPATING CENTERS:**
  Lewis Research Center
  Los Alamos National Laboratory
- **FY 1989 BUDGET: $10 MILLION**
  (NASA portion only)

JCM-0766



PATHFINDER RESOURCE PROCESSING PILOT PLANT

OAST

TECHNOLOGIES
• MATERIALS ANALYSIS SENSORS • MECHANICAL SEPARATION/EXTRACTION • ELECTRO-CHEMICAL SEPARATION/EXTRACTION • ROBOTIC MATERIALS COLLECTION/HANDLING

MISSION APPLICATIONS
• LUNAR OUTPOST RESOURCE PLANT • MARS RESOURCE PLANT • OTHER SOLAR SYSTEM RESOURCE UTILIZATION

JCM-0058

PATHFINDER RESOURCE PROCESSING PILOT PLANT

OAST

PROGRAM MANAGEMENT

- LEAD OAST DIVISION:
  Materials and Structures Division
- LEAD NASA FIELD CENTER:
  Johnson Space Center
- PARTICIPATING CENTERS:
  Jet Propulsion Laboratory
- INITIATION DEFERRED TO 1990

JCM-0767

PATHFINDER
OPTICAL COMMUNICATIONS

OAST

TECHNOLOGIES

- ACQUISITION & TRACKING SYSTEMS
- CONTROL SYSTEMS
- TELESCOPE/LASER SYSTEMS

MISSION APPLICATIONS

- LUNAR OUTPOST
- PILOTED MARS EXPEDITIONS
- ROBOTIC SOLAR SYSTEM EXPLORATION

JCM-0056

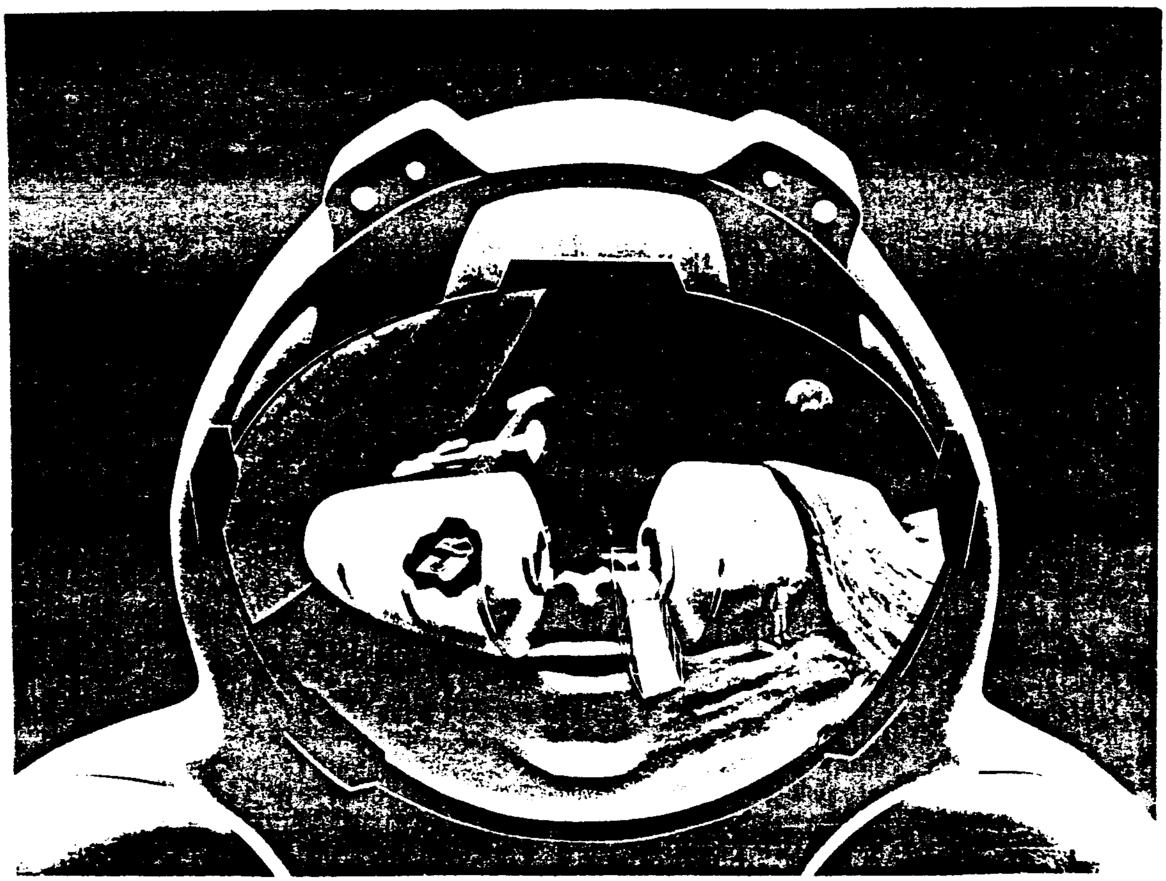
PROGRAM MANAGEMENT

- **LEAD OAST DIVISION:**
  Information Sciences & Human Factors Division

- **PARTICIPATING CENTERS:**
  Goddard Space Flight Center
  Jet Propulsion Laboratory

- **INITIATION DEFERRED TO 1990**

JCM-0768



PATHFINDER PROGRAM AREA
HUMANS IN SPACE

OAST

TECHNOLOGY NEEDS

- SPACE-MAINTAINABLE SURFACE SUITS FOR MOON/MARS/PHOBOS APPLICATIONS
- SPACE-MAINTAINABLE EVA SUITS FOR DEEP SPACE TRANSIT APPLICATIONS
- COUNTERMEASURES FOR MICROGRAVITY EFFECTS OF LONG-DURATION HUMAN MISSIONS
- COUNTERMEASURES FOR RADIATION EFFECTS OF LONG-DURATION HUMAN MISSIONS
- ADVANCED HUMAN-MACHINE INTERFACES AND SYSTEMS
- IMPROVED LIFE SUPPORT SYSTEMS (INCLUDING BOTH PHYSICAL-CHEMICAL ENVIRONMENTAL CONTROL AND BIOGENERATIVE LIFE SUPPORT SYSTEMS)

JCM-0753

PATHFINDER
HUMANS IN SPACE

OAST

ELEMENT PROGRAMS

- EXTRAVEHICULAR ACTIVITY (EVA)/SUIT
- SPACE HUMAN FACTORS
- HUMAN PERFORMANCE (& HEALTH)
- PHYSICAL-CHEMICAL LIFE SUPPORT
- BIOREGENERATIVE LIFE SUPPORT
- COUNTERMEASURES TECHNOLOGY

JCM 0847

PATHFINDER
EXTRAVEHICULAR ACTIVITY/SUIT

OAST

TECHNOLOGIES
• SUIT COMPONENTS (Miniaturized) • MATERIALS • THERMAL MANAGEMENT SYSTEMS • ENVIRONMENTAL COUNTERMEASURES • PORTABLE LIFE SUPPORT SYSTEMS

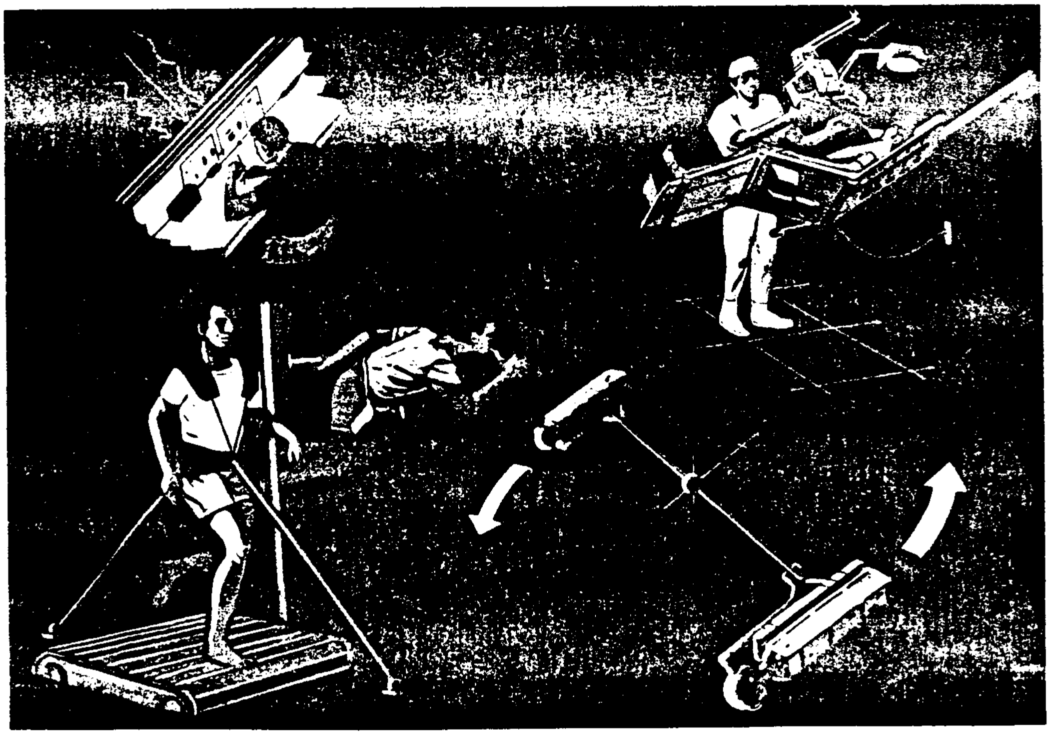
MISSION APPLICATIONS
• LUNAR OUTPOST • PILOTED MARS EXPEDITION • ADVANCED EARTH-ORBIT OPERATIONS

JCM-0062

PROGRAM MANAGEMENT

- **LEAD OAST DIVISION:**
  Information Sciences & Human Factors Division
- **LEAD NASA FIELD CENTERS:**
  Ames Research Center
- **PARTICIPATING CENTERS:**
  Johnson Space Center
  Langley Research Center

JCM-0769



PATHFINDER
HUMAN PERFORMANCE

OAST

SUB-ELEMENTS

- SPACE HUMAN FACTORS
- ARTIFICAL GRAVITY
- RADIATION (EFFECTS & COUNTERMEASURES)

MISSION APPLICATIONS

- LUNAR OUTPOST/BASE
- PILOTED MARS SYSTEM MISSIONS

JCM 0846

PATHFINDER
SPACE HUMAN FACTORS

OAST

SUB-ELEMENTS

- HUMAN-MACHINE INTERFACES
- HUMAN PERFORMANCE MODELS
- HUMAN-AUTOMATION-ROBOTIC SYSTEMS

MISSION APPLICATIONS

- LUNAR OUTPOST/BASE
- PILOTED MARS SYSTEM MISSIONS

JCM 0845

PATHFINDER
SPACE HUMAN FACTORS

OAST

PROGRAM MANAGEMENT

- **LEAD OAST DIVISION:**
  Information Sciences & Human Factors Division

- **PARTICIPATING CENTERS:**
  Ames Research Center
  Johnson Space Center

JCM-0770

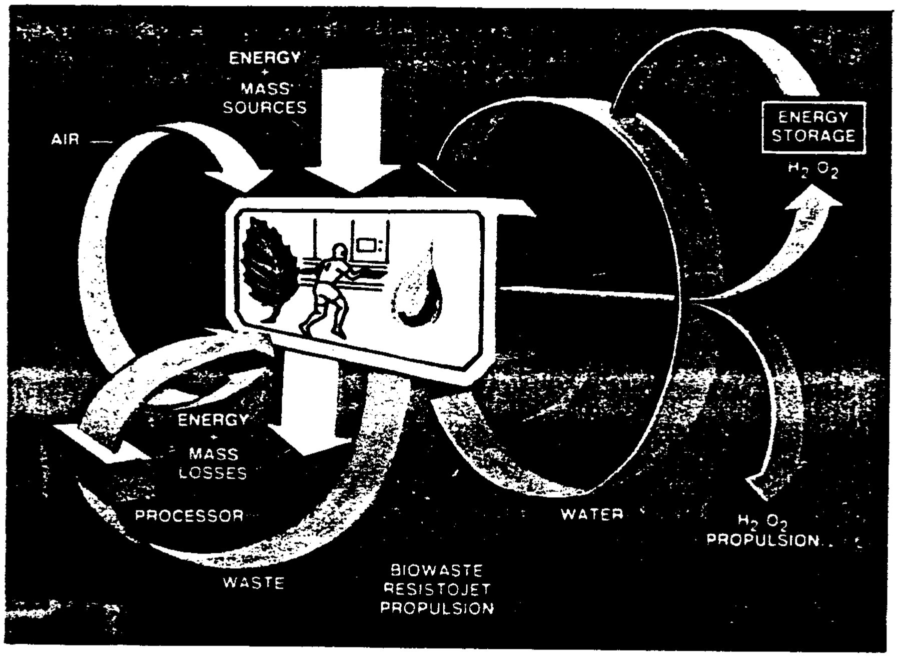
PATHFINDER
COUNTERMEASURES TECHNOLOGY

OAST

SUB-ELEMENTS
• ARTIFICIAL GRAVITY SYSTEMS TECHNOLOGY • RADIATION PROTECTION

MISSION APPLICATIONS
• LUNAR OUTPOST/BASE • PILOTED MARS SYSTEM MISSIONS

JCM-0842



PATHFINDER
PHYSICAL-CHEMICAL LIFE SUPPORT

OAST

SUB-ELEMENTS
• LIFE SUPPORT SYSTEM/PROCESS MODELS • AIR REVITALIZATION • WATER RECLAMATION • WASTE TREATMENT

MISSION APPLICATIONS
• LUNAR OUTPOST/BASE • PILOTED MARS SYSTEM MISSIONS

JCM-0844

PATHFINDER
PHYSICAL-CHEMICAL LIFE SUPPORT

OAST

PROGRAM MANAGEMENT

- **LEAD OAST DIVISION:**
  Propulsion, Power, and Energy Division
- **LEAD NASA FIELD CENTER:**
  Ames Research Center
- **PARTICIPATING CENTERS:**
  Johnson Space Center
  Jet Propulsion Laboratory

JCM-0771

PATHFINDER
BIOREGENERATIVE LIFE SUPPORT

OAST

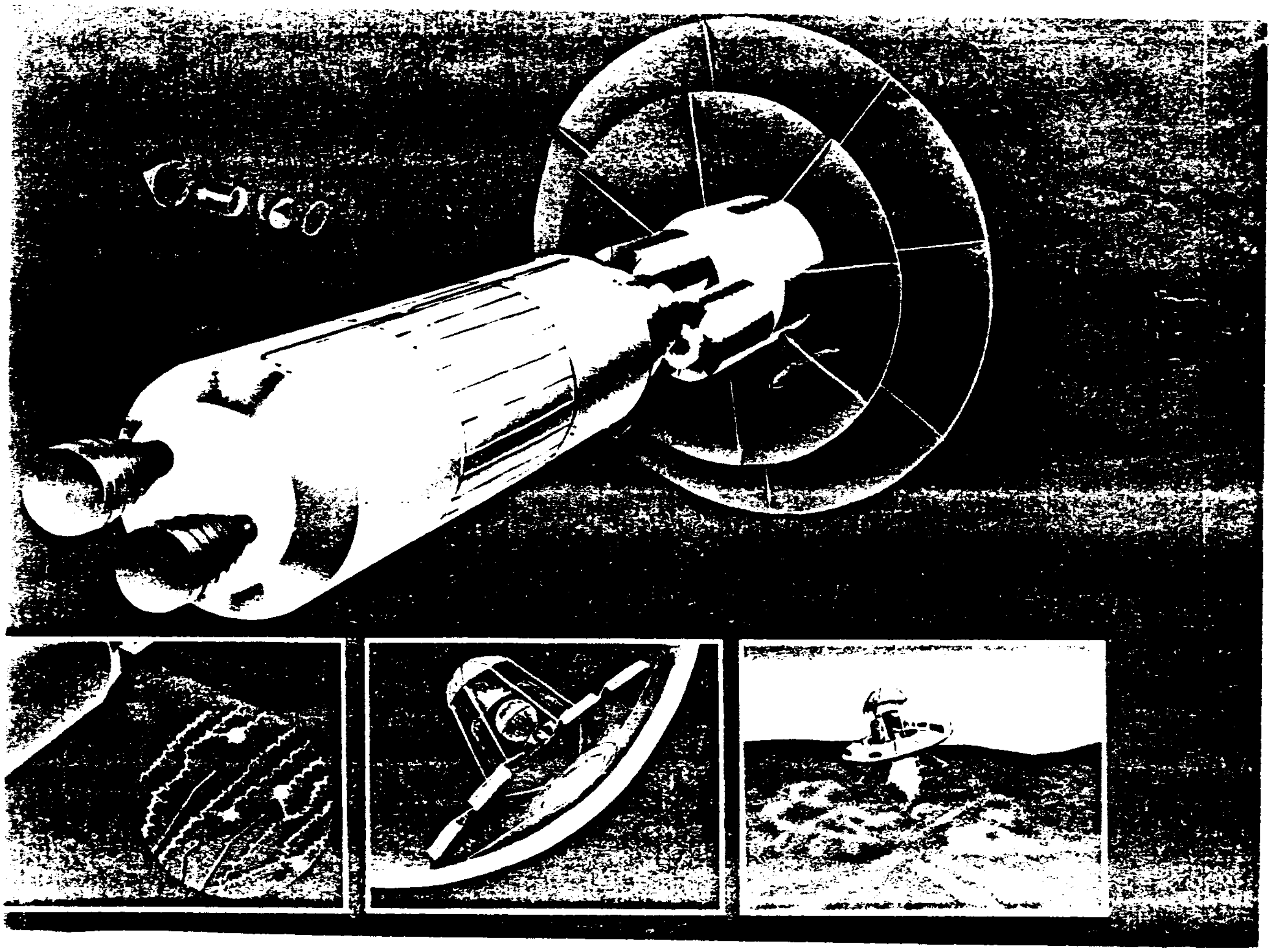
SUB-ELEMENTS

- BIOMASS PRODUCTION
- FOOD PROCESSING
- RESOURCE RECYCLING/RECOVERY
- CELSS MONITORING AND CONTROL

MISSION APPLICATIONS

- LUNAR OUTPOST/BASE
- MARS SYSTEM OUTPOST

JCM-0843



PATHFINDER PROGRAM AREA
SPACE TRANSFER

OAST

TECHNOLOGY NEEDS

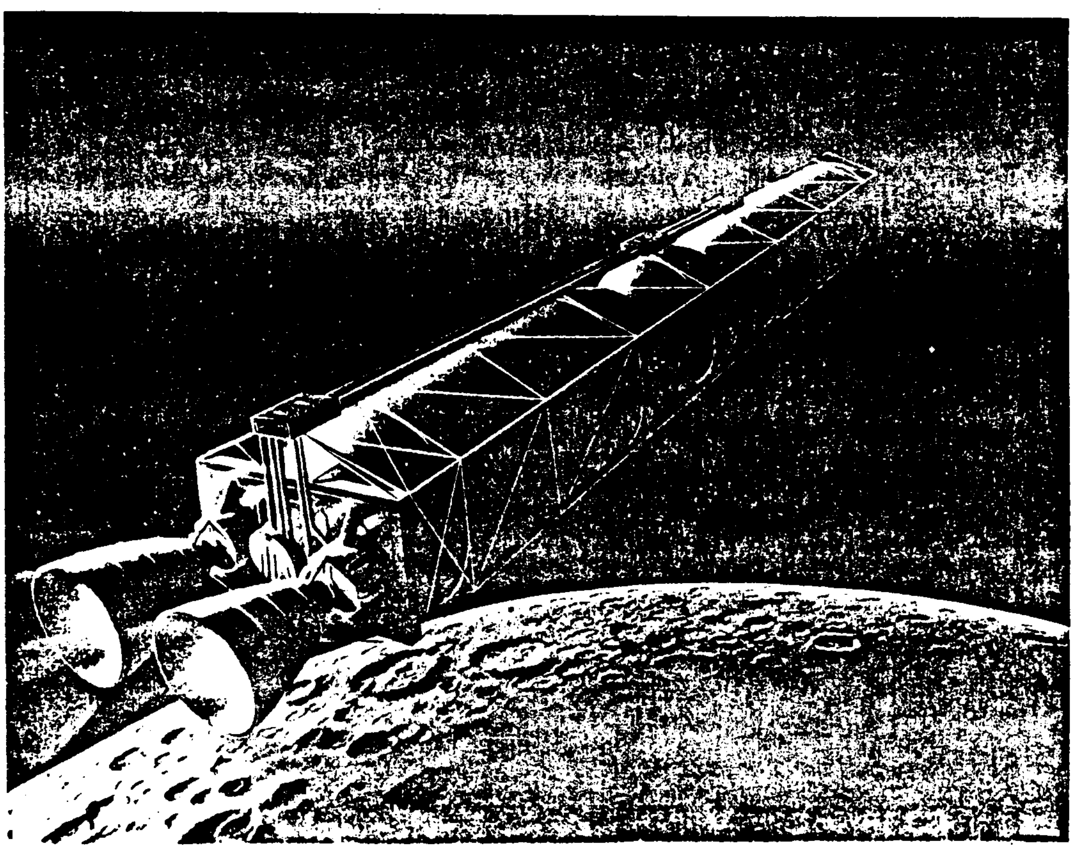
- ADVANCED CHEMICAL PROPULSION SYSTEMS (DESIGNED FOR SPACE-BASING/MAINTENANCE)
- HIGH-THRUST IN-SPACE PROPULSION FOR HUMAN MISSION STAGING
- LUNAR-LEO AND INTERPLANETARY AERO-BRAKING (TPS, GN&C, AEROTHERMODYNAMICS)
- DESCENT/ASCENT PROPULSION FOR MOON/MARS APPLICATIONS
- HIGH-EFFICIENCY ELECTRIC PROPULSION FOR CARGO TRANSFER

PATHFINDER PROGRAM AREA
SPACE TRANSFER

ELEMENT PROGRAMS

- CHEMICAL TRANSFER PROPULSION
- HIGH-ENERGY AEROBRAKING
- CARGO VEHICLE PROPULSION

JCM-0748



PATHFINDER
CHEMICAL TRANSFER PROPULSION

OAST

TECHNOLOGIES
• LIQUID OXYGEN/HYDROGEN ENGINES
• HIGH-HEAT COMBUSTERS
• HIGH-PRESSURE TURBO-MACHINERY
• INTEGRATED DIAGNOSTICS/CONTROLS

MISSION APPLICATIONS
• LUNAR OUTPOST OPERATIONS VEHICLES
• ROBOTIC SOLAR SYSTEM EXPLORATION
• PILOTED MARS EXPEDITION
• ADVANCED EARTH-ORBIT OPERATIONS

JCM-0065

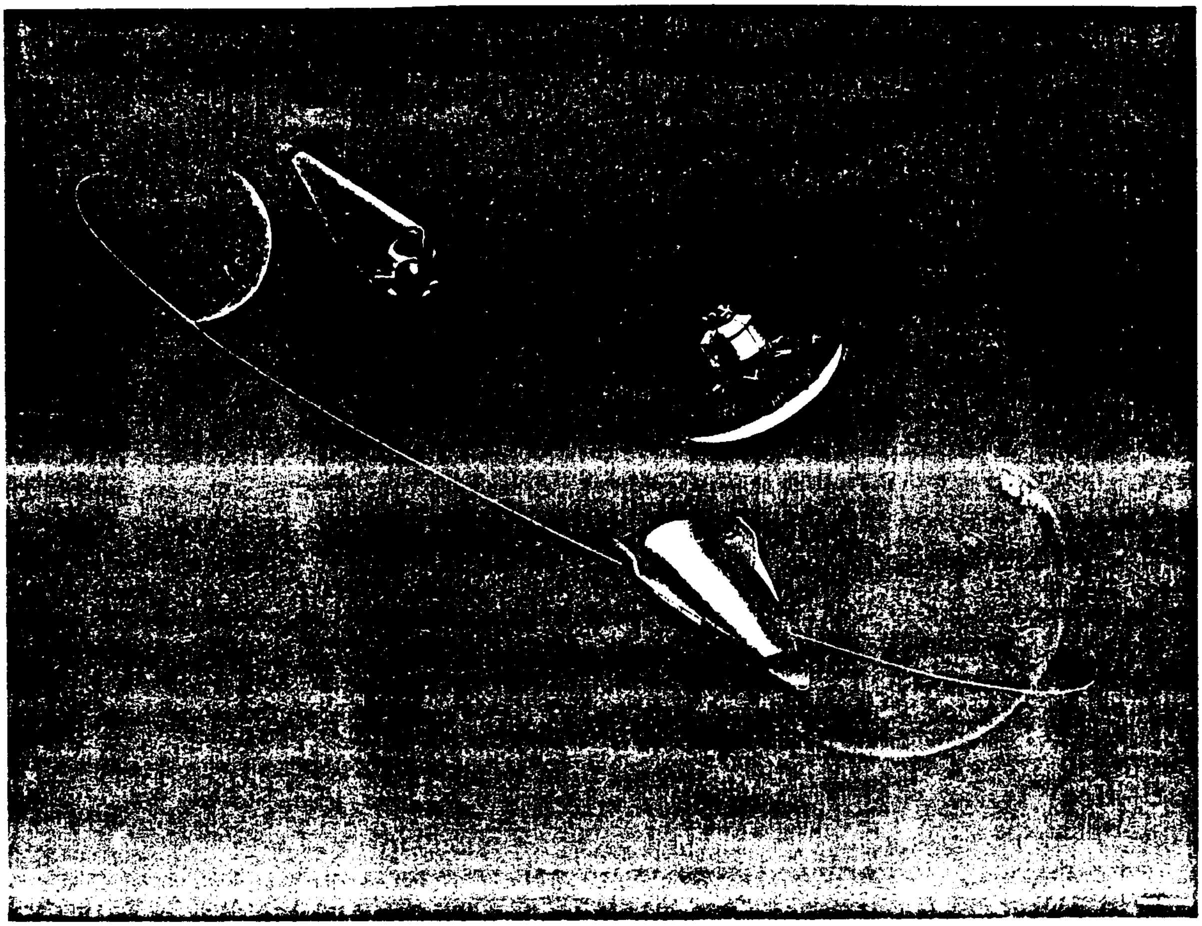
PATHFINDER
CHEMICAL TRANSFER PROPULSION

OAST

PROGRAM MANAGEMENT

- LEAD OAST DIVISION: Propulsion, Power, and Energy Division
- LEAD NASA FIELD CENTER: Lewis Research Center
- PARTICIPATING CENTERS: Marshall Space Flight Center (Not funded in FY'89)
- FY 1989 BUDGET: $4 MILLION

JCM-0773



PATHFINDER
HIGH-ENERGY AEROBRAKING

O-A-S-T

TECHNOLOGIES
• AEROBRAKE CONFIGURATIONS • AEROTHERMODYNAMICS • GN&C (On-Board, Autonomous, Adaptive) • THERMAL PROTECTION SYSTEMS

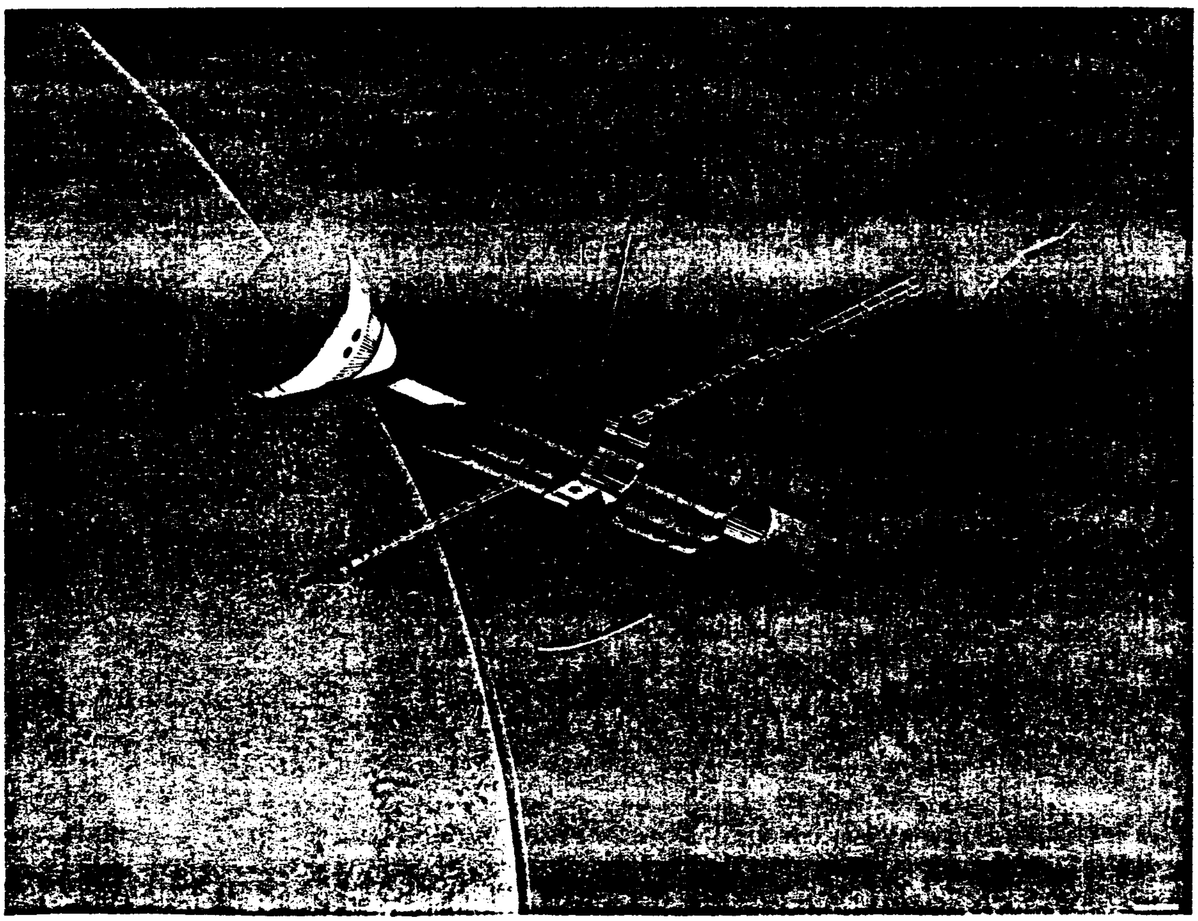
MISSION APPLICATIONS
• LUNAR OUTPOST OPERATIONS • ROBOTIC/PILOTED MARS EXPEDITION • ROBOTIC SOLAR SYSTEM EXPLORATION

JCM-0067

PROGRAM MANAGEMENT

- **LEAD OAST DIVISION:**
  Aerodynamics Division
- **LEAD NASA FIELD CENTER:**
  Langley Research Center
- **PARTICIPATING CENTERS:**
  Ames Research Center
  Johnson Space Center
  Jet Propulsion Laboratory
- **FY 1989 BUDGET: $1.5 MILLION**

JCM-0772



PATHFINDER
CARGO VEHICLE PROPULSION

OAST

TECHNOLOGIES

- MAGNETOPLASMADYNAMIC THRUSTERS (MPD) (e.g., Cathodes, Controls, Magnetic Fields, High Power Level Systems)
- ION ENGINES (Testing)
- LONG-LIFE TESTING

MISSION APPLICATIONS

- LUNAR OUTPOST OPERATIONS (OTV/Ion)
- PILOTED MARS EXPEDITION (Cargo Vehicle)
- ROBOTIC SOLAR SYSTEM EXPLORATION (Ion)

JCM-0066

PATHFINDER
CARGO VEHICLE PROPULSION

OAST

PROGRAM MANAGEMENT

- LEAD OAST DIVISION: Propulsion, Power, and Energy Division
- LEAD NASA FIELD CENTER: Lewis Research Center
- PARTICIPATING CENTERS: Jet Propulsion Laboratory
- INITIATION DEFERRED TO 1990

JCM-0774

PATHFINDER PROGRAM AREA
MISSION STUDIES

OAST

OBJECTIVES

- DEFINE MISSION OPTIONS FOR HUMAN EXPLORATION
- IDENTIFY TECHNOLOGY NEEDS
- DEVELOP INFORMATION TO SUPPORT NATIONAL DECISIONS

JCM-0749

PATHFINDER SUMMARY

OAST

- **RESEARCH AND TECHNOLOGY TO ENABLE FUTURE SPACE MISSIONS**

  FOCUS ON SOLAR SYSTEM EXPLORATION

  Piloted Exploration Expeditions

  Long-Duration Human Operations In Space

  Robotic Exploration (Science & Precursor)

- **SUPPORT FOR U.S. TECHNOLOGICAL LEADERSHIP IN SPACE AND ON EARTH**

- **PATHFINDER STARTED IN FY'89**

  STRONG MULTI-YEAR PLANS ESTABLISHED

  FIRST YEAR BUDGET OF $40 MILLION

JCM-0755

PATHFINDER PROGRAM DELIVERABLES: SUMMARY

OAST

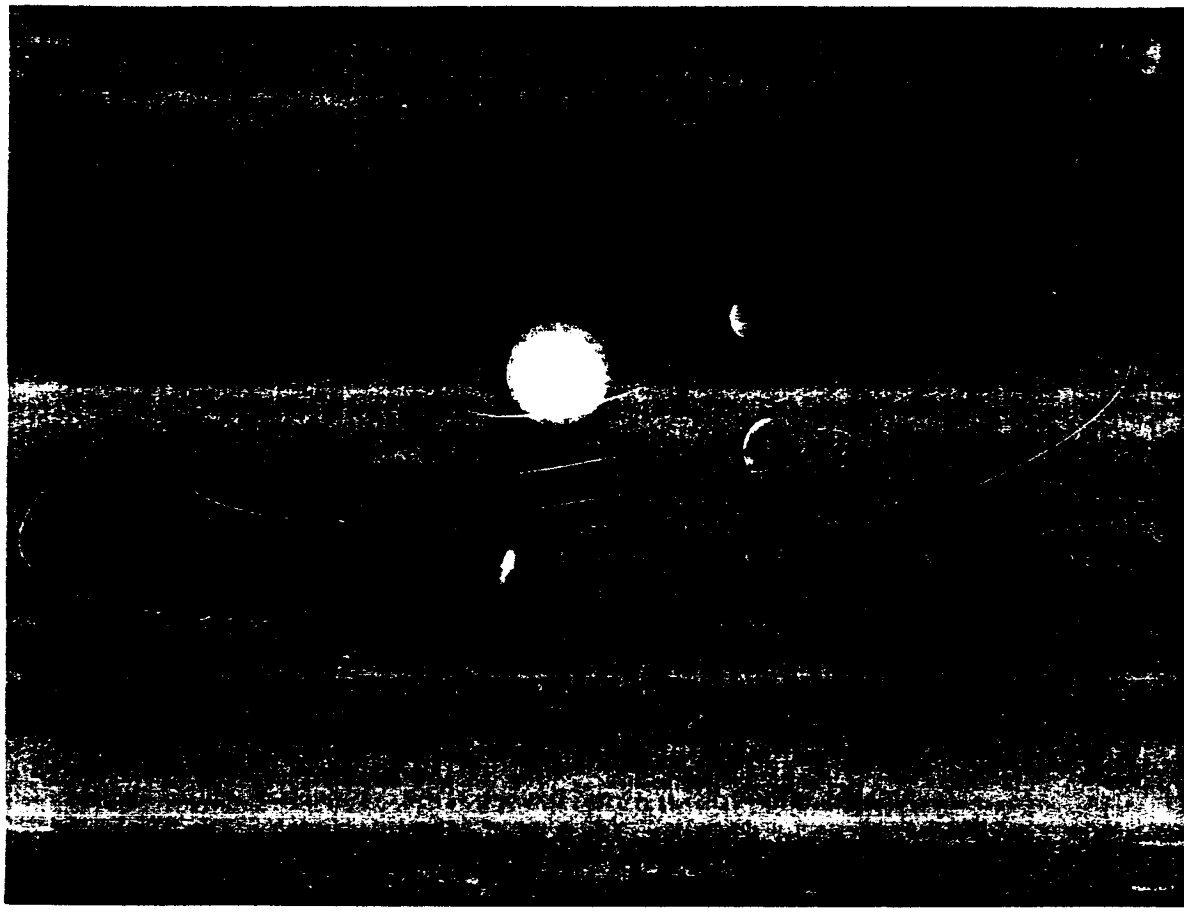
1991-1993

- PHASE I TECHNOLOGY CONCEPTS AND COMPONENT-LEVEL PROOF-OF-CONCEPT, SOME BREADBOARDS
- PRELIMINARY TECHNOLOGY AND ENGINEERING DATA TO SUPPORT NATIONAL EXPLORATION DECISIONS
- EARLY TECHNOLOGY TRANSFER TO SUPPORT ROBOTIC & PRECURSOR EXPLORATION MISSIONS

1996-1998

- INTEGRATED BREADBOARD TECHNOLOGY RESEARCH AND DEMONSTRATIONS, INCLUDING FLIGHT DEMOS
- DETAILED TECHNOLOGY AND ENGINEERING DATA AND TOOLS TO SUPPORT EXPLORATION MISSION DESIGN
- PHASE II TECHNOLOGY CONCEPTS AND COMPONENT-LEVEL PROOF-OF-CONCEPT, SOME BREADBOARDS
- CONTINUING TECHNOLOGY TRANSFER TO SUPPORT EXPLORATION MISSION SYSTEM DEVELOPMENT

JCM-0822



Office of
Aeronautics and
Space
Technology

PROJECT PATHFINDER CARGO VEHICLE PROPULSION PROGRAM

Presentation to

JOINT MEETING ON POWER AND PROPULSION TECHNOLOGIES FOR CARGO VEHICLE PROPULSION

James R. Stone
Program Element Manager
February 8, 1989

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

BACKGROUND

- COST OF DELIVERING PROPELLANT TO LEO IS BECOMING A DOMINANT FACTOR FOR CHALLENGING MISSIONS
  - PROPELLANT MASS FRACTION:
    43 PERCENT FOR GALILEO
    76 PERCENT FOR CRAF
- HIGH SPECIFIC IMPULSE (OVER 4000 SEC) ELECTRIC PROPULSION OFFERS MAJOR PROPELLANT MASS SAVINGS
  - ELIMINATES AT LEAST 3 HLLV LAUNCHES FOR MARS CARGO VEHICLE

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PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

LUNAR & PLANETARY MISSION PROPULSION REQUIREMENTS

OPPORTUNITIES FOR ELECTRIC PROPULSION

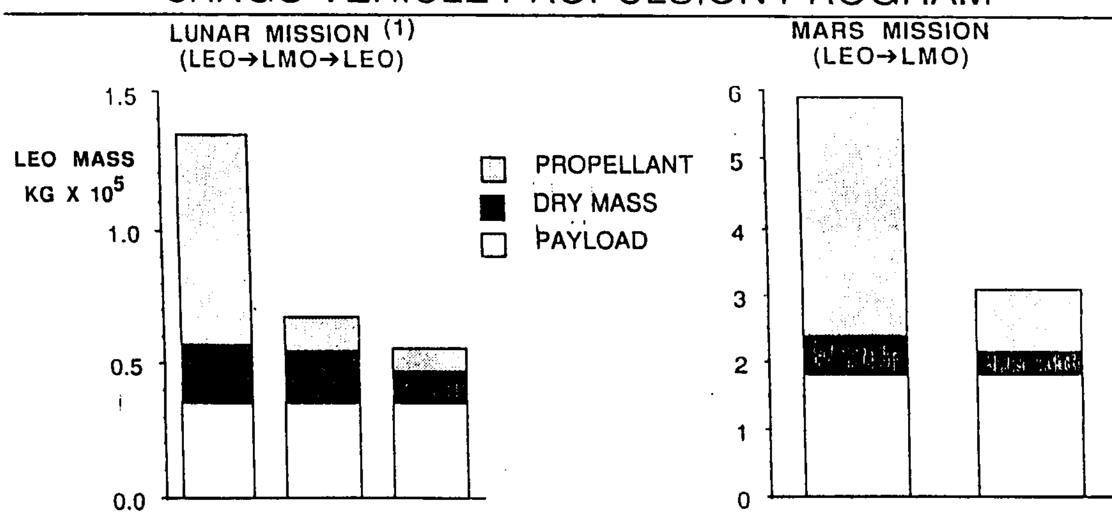
AN ENORMOUS RANGE OF MISSION CONCEPTS & REQUIREMENTS EXISTS

- O PRECURSOR VS LATER MISSIONS
- O CREW & CARGO SPLIT OR UNSPLIT
- O CREW TRIP TIME CONSTRAINTS
- O DIRECT VS "DEPOT" APPROACHES

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

CARGO VEHICLE PROPULSION PROGRAM



	Lunar			Mars	
• Propulsion	H_2/O_2	NEPS	SEPS	H_2/O_2	NEPS
• I_{sp} sec	475	5000	5000	480	5000
• Power, MW	-	1	0.3	-	4
• Trip Time,Days	10	257	769	210	700
• Aerobraking	Yes	No	No	Yes	No

ELECTRIC PROPULSION PROMISES SIGNIFICANT LEO MASS REDUCTIONS

(1) Data from B. Palaszewski of JPL

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

LUNAR AND MARS CARGO VEHICLES

O SUB—YEAR MARS MISSIONS REQUIRE ABOUT:

— 1000 MWe FROM LEO

— 1—5 MWe FROM LLO

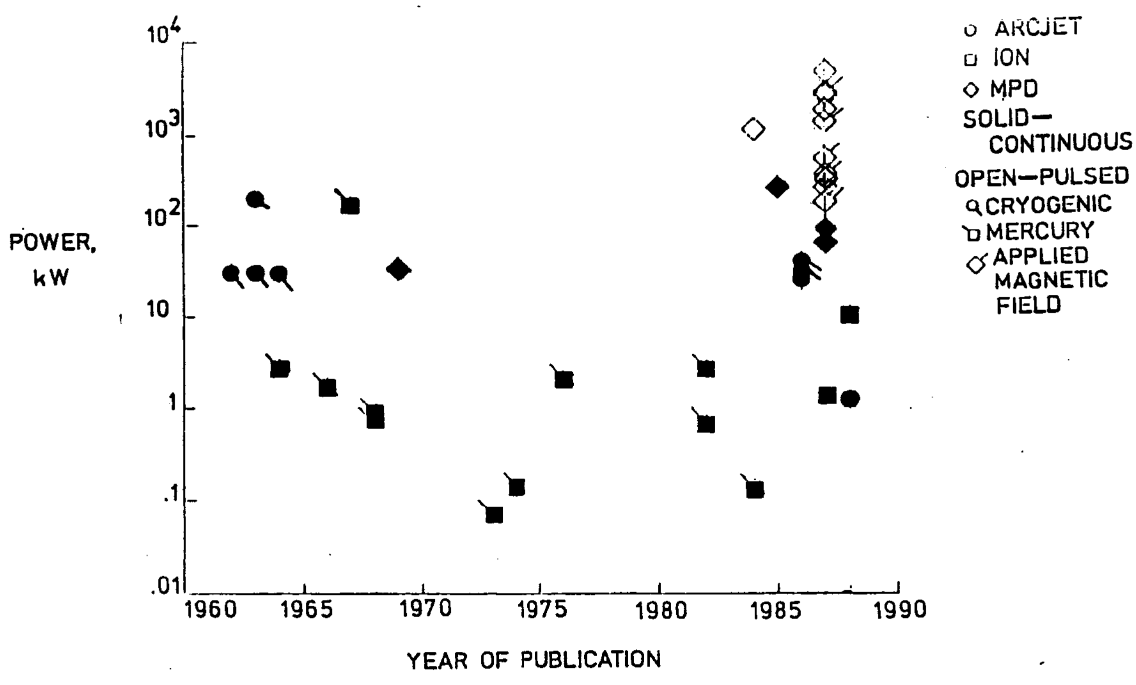
O SUB—YEAR LUNAR MISSIONS REQUIRE ABOUT:

—0.5 — 1MWe FROM LEO

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

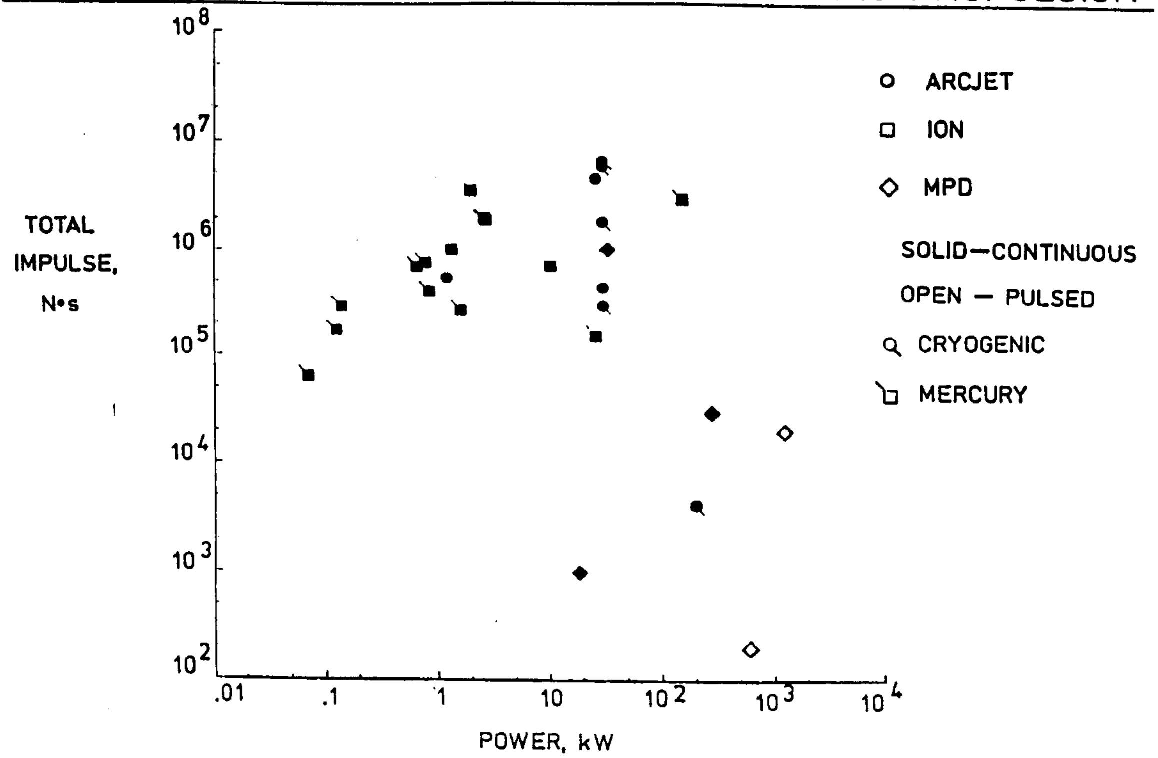
HISTORICAL TREND OF E.P. POWER LEVELS



PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

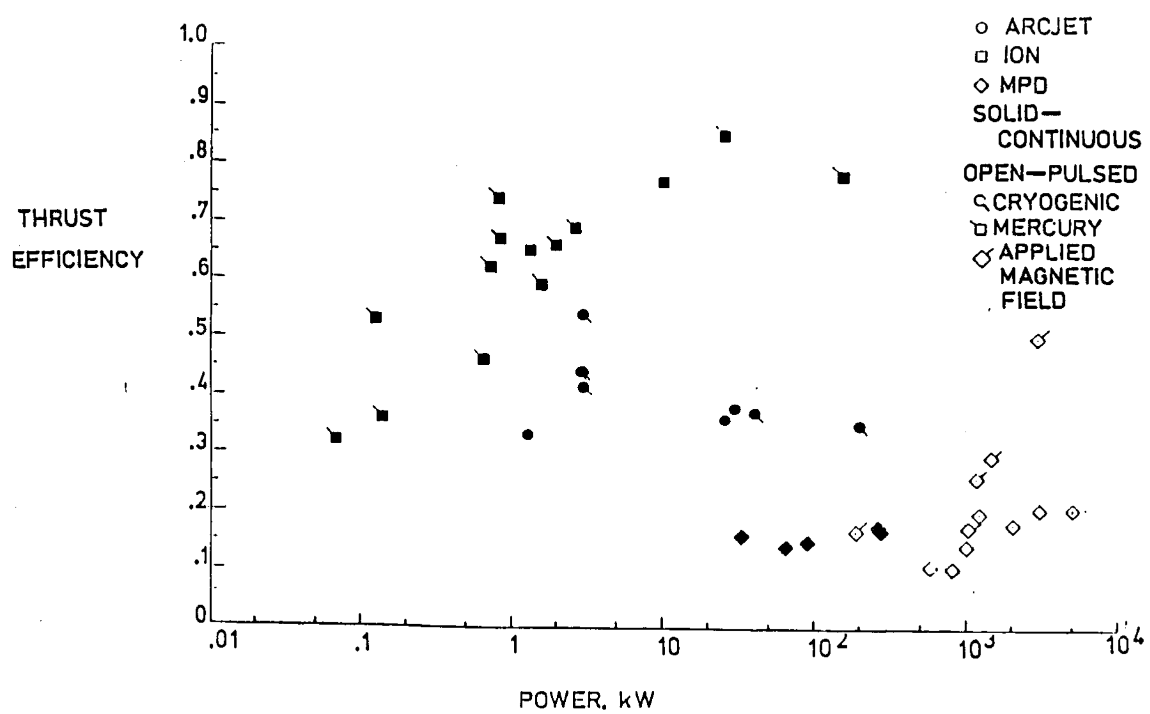
DEMONSTRATED TOTAL IMPULSE FOR ELECTRIC PROPULSION



PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

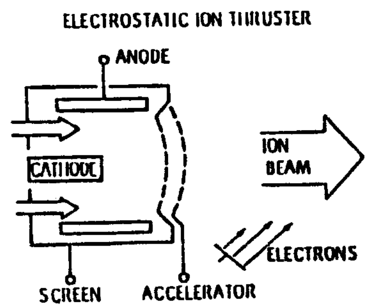
DEMONSTRATED EFFICIENCY FOR ELECTRIC PROPULSION



PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

ION THRUSTER



DEMONSTRATED PERFORMANCE

O MAXIMUM POWER, KW	300
O EFFICIENCY	0.5 TO 0.7
O LIFE, HR.	4000 TO 10,000 @ 3 KW
O TOTAL IMPULSE NS	2×10^{6}

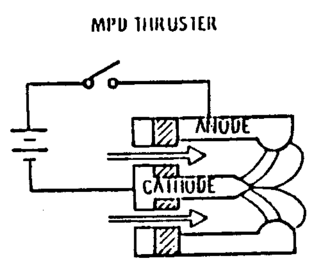
CHARACTERISTICS

- O I_{SP} FROM 3000 TO > 10,000 S
- O MULTIPLE PROPELLANTS
- O HIGH POWER CAPABILITY
- O STEADY STATE

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

MPD THRUSTER



DEMONSTRATED PERFORMANCE

	SELF-FIELD	APPLIED FIELD
O MAXIMUM POWER, KW	5000 (270 CW)	70
O EFFICIENCY	0.1 TO 0.5	0.1 TO 0.5
O LIFE, HR	1 (@ 200 KW)	500 (@ 32 KW)
O TOTAL IMPULSE, Ns	3×10^{4}	9×10^{5}

CHARACTERISTICS

- o Isp FROM 1000 TO 10000 S
- o THRUST LEVELS TO 100 N
- o MULTIPLE PROPELLANTS
- o PULSED OR STEADY STATE

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

PROGRAM GOALS AND OBJECTIVES

- ESTABLISH FEASIBILITY OF ELECTRIC THRUSTERS ADEQUATE FOR MAJOR MARS/LUNAR MISSIONS
  - SPECIFIC IMPULSE > 4000 SEC
  - THRUST EFFICIENCY > 0.60
  - PROPULSION SYSTEM SPECIFIC MASS < 10 KG/KW
  - SCALABILITY TO MULTI-MEGAWATT POWER LEVEL
- ADVANCE RAPID DURABILITY/LIFE EVALUATON TECHNIQUES TO ESTABLISH FEASIBILITY OF 10^8 N•S TOTAL IMPULSE
- SELECTION OF MOST PROMISING CANDIDATE SYSTEM FOR FURTHER DEVELOPMENT

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

PROGRAM PLANNING CONSIDERATIONS

O MISSION PERFORMANCE(S) VS TECHNOLOGY LEVEL NEEDED

O HIGH FIDELITY LIFE & PERFORMANCE VERIFICATIONS REQUIRED & PROGRAM COST DRIVER

O VERY EARLY ASSESSMENTS OF COST/SCHEDULE DRIVERS ESSENTIAL

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

PROGRAM DESCRIPTION

- 0 PHASE I: PERFORMANCE AND DURABILITY TECHNOLOGY ADVANCEMENT (5 YEARS)
- 0 SELECTION OF MOST PROMISING PROPULSION CONCEPT
- 0 PHASE II: DEMONSTRATE PERFORMANCE AND LIFE AT HIGH POWER, AND DEFINE FLIGHT TEST REQUIREMENTS (5? YEARS)
- 0 PHASE III: FLIGHT VALIDATION (TBD)

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

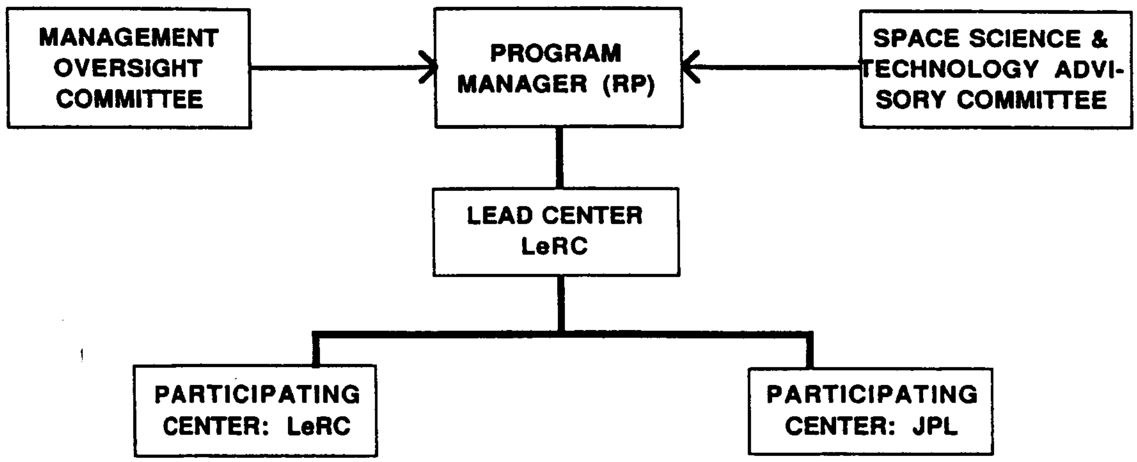
OAST

MANAGEMENT PLAN

- 0 MANAGEMENT STRUCTURE
- 0 WORK BREAKDOWN STRUCTURE
- 0 SCHEDULE
- 0 RESOURCES

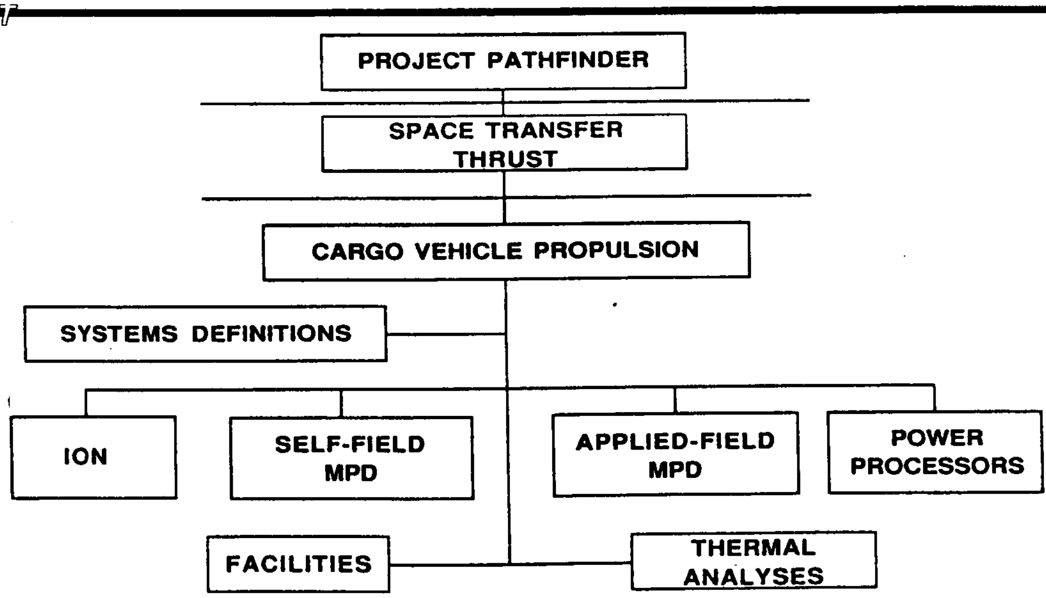
CARGO VEHICLE PROPULSION MANAGEMENT STRUCTURE

OAST



CARGO VEHICLE PROPULSION WORK BREAKDOWN STRUCTURE

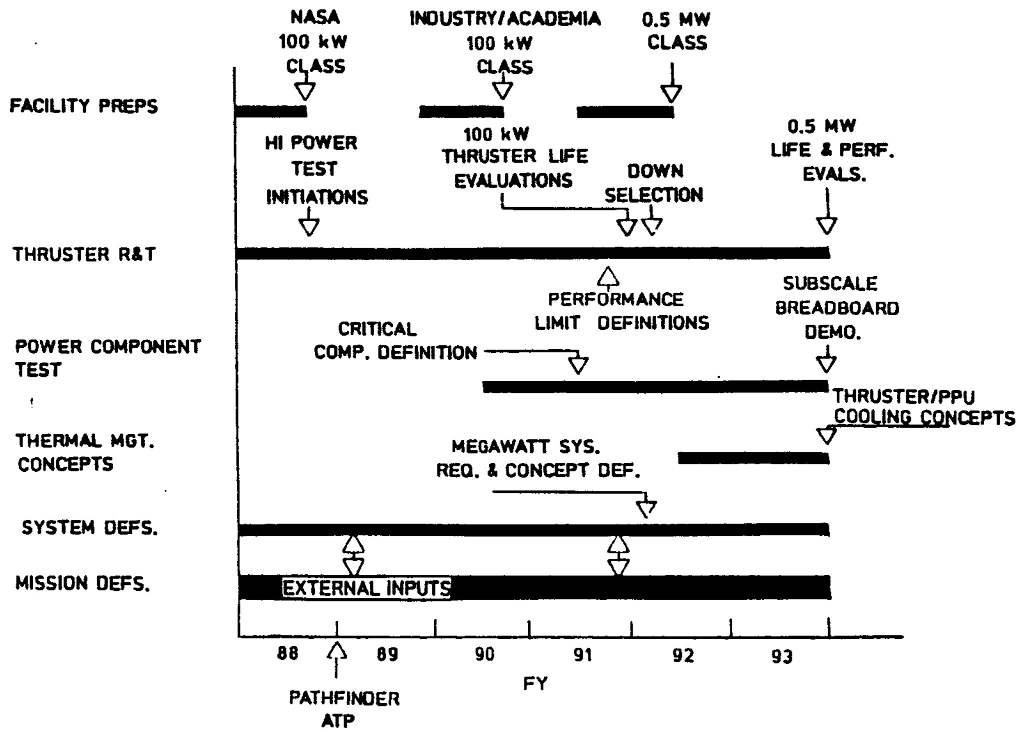
OAST



PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

ORIGINAL SCHEDULE



PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

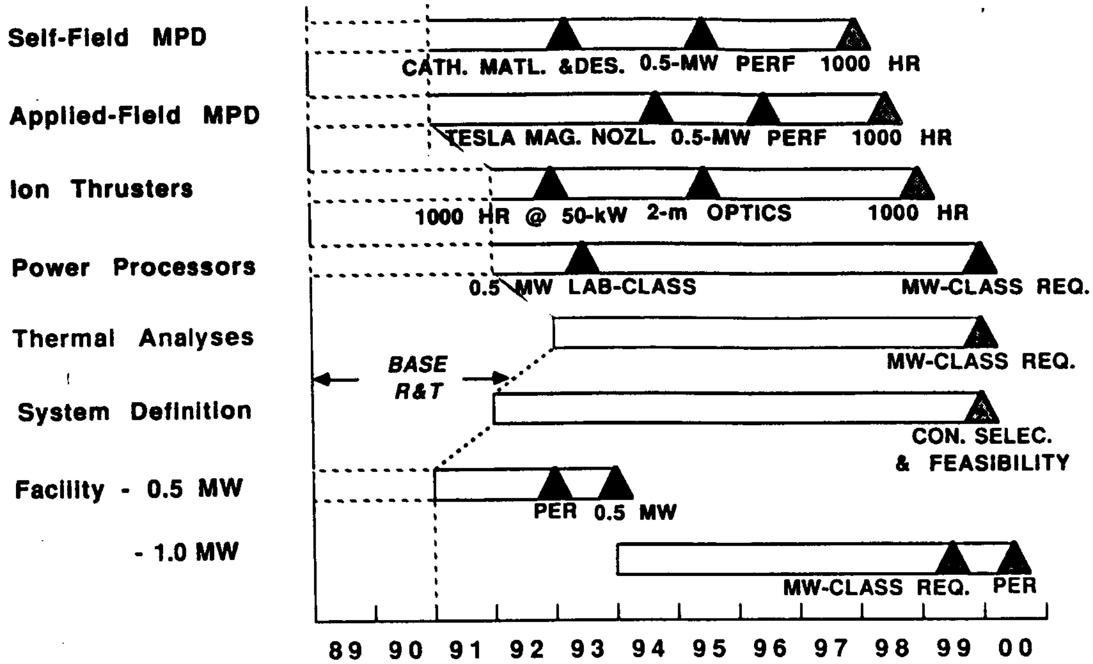
HIGH PERFORMANCE CARGO VEHICLE PROPULSION 5-YEAR (PHASE I) CYCLE RESOURCE ALLOCATION

RESOURCE ALLOCATION	FY 89	FY 90	FY 91	FY 92	FY 93	FY 94
FUNDING, M$	0.0	0.0	1.0	2.0	3.0	3.0
NASA WK-YRS	0.0	0.0	2.0	3.0	4.0	4.0

PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

PROGRAM SCHEDULE/MILESTONES



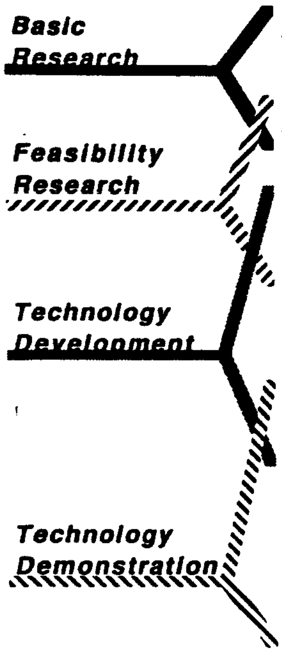
PROJECT PATHFINDER
CARGO VEHICLE PROPULSION

OAST

TECHNOLOGY READINESS LEVELS

DELIVERABLE	TECHNOLOGY READINESS LEVEL CURRENT (1988)	PHASE I (1999)	PHASE II (2005)
SELF-FIELD MPD	3	5	–
APPLIED-FIELD MPD	3	5	–
ION	4	5	–
POWER PROCESSOR	3	5	–
THERMAL CONTROL	2	3	–
ELECTRIC PROPULSION SYSTEM	2	5	6

TECHNOLOGY READINESS LEVELS
AND PROGRAM PHASES



LEVEL 1 - *BASIC PRINCIPLES OBSERVED & REPORTED*

LEVEL 2 - *TECHNOLOGY CONCEPT/APPLICATION FORMULATED*

LEVEL 3 - *ANALYTICAL & EXPERIMENTAL CRITICAL FUNCTION AND/OR CHARACTERISTIC PROOF-OF-CONCEPT*

LEVEL 4 - *COMPONENT AND/OR BREADBOARD VALIDATION IN LABORATORY*

LEVEL 5 - *COMPONENT AND/OR BREADBOARD DEMONSTRATION IN RELEVANT ENVIRONMENT*

LEVEL 6 - *SYSTEM VALIDATION MODEL DEMONSTRATED IN SIMULATED ENVIRONMENT*

LEVEL 7 - *SYSTEM VALIDATION MODEL DEMONSTRATED IN SPACE*

ELECTRIC PROPULSION TECHNOLOGY STATUS

PRESENTATION TO THE JOINT MEETING ON POWER AND PROPULSION TECHNOLOGIES FOR CARGO VEHICLE PROPULSION

WASHINGTON, D.C. FEBRUARY 8, 1989

JAMES S. SOVEY, NASA LERC
DAVID KING, JPL

SPACE PROPULSION TECHNOLOGY DIVISION

CARGO VEHICLE PROPULSION

ELECTRIC PROPULSION

OUTLINE

I	BACKGROUND	JIM SOVEY
	• EP MISSION IMPACT	
	• EP SYSTEM REQUIREMENTS	
	• SELECTED CONCEPTS	
	• EP STATUS SUMMARY	
II	TECHNOLOGY STATUS	
	• ION	JIM SOVEY
	• MPD	DAVE KING
III	SUMMARY	DAVE KING

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MISSION IMPACT

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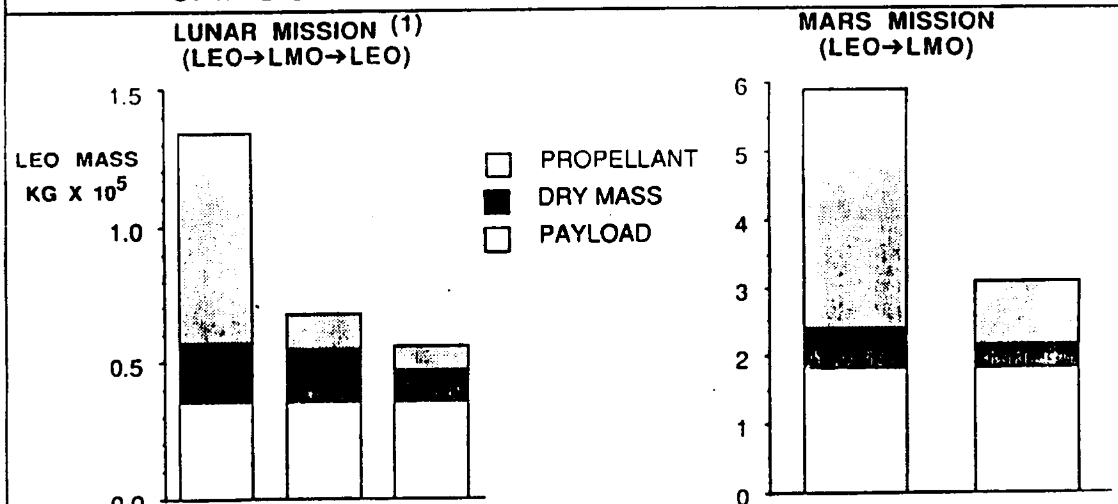
CARGO VEHICLE PROPULSION PROGRAM



	Lunar			Mars	
• Propulsion	H_2/O_2	NEPS	SEPS	H_2/O_2	NEPS
• I_{sp} sec	475	5000	5000	480	5000
• Power, MW	-	1	0.3	-	4
• Trip Time,Days	10	257	769	210	700
• Aerobraking	Yes	No	No	Yes	No

ELECTRIC PROPULSION PROMISES SIGNIFICANT LEO MASS REDUCTIONS

(1) Data from B. Palaszewski of JPL

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SYSTEM REQUIREMENTS FOR LUNAR AND MARS CARGO VEHICLES

- PERFORMANCE
- POWER SCALING
- TOTAL IMPULSE

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PRELIMINARY ELECTRIC PROPULSION REQUIREMENTS

- SPECIFIC MASS, SPECIFIC IMPULSE AND THRUSTER SYSTEM EFFICIENCY DEFINE MASS IN LEO AND TRIP TIME
- REQUIREMENTS
  - * MARS CARGO VEHICLE POWER AND PROPULSION SPECIFIC MASS <10 KG/KW AT 4 TO 10 MW
  - * LUNAR CARGO VEHICLE POWER LEVEL $\approx$ 1MW
  - * SPECIFIC IMPULSE $\approx$ 5000 s FOR MARS CARGO VEHICLE
  - TO MINIMIZE MASS IN LEO AND TRIP TIME

    ION: EFFICIENCY > 0.75

    MPD: EFFICIENCY > 0.60
  - TOTAL IMPULSE PER THRUSTER: 1×10^8 TO 5×10^8 NS

*DATA FROM B. PALASZEWSKI OF JPL

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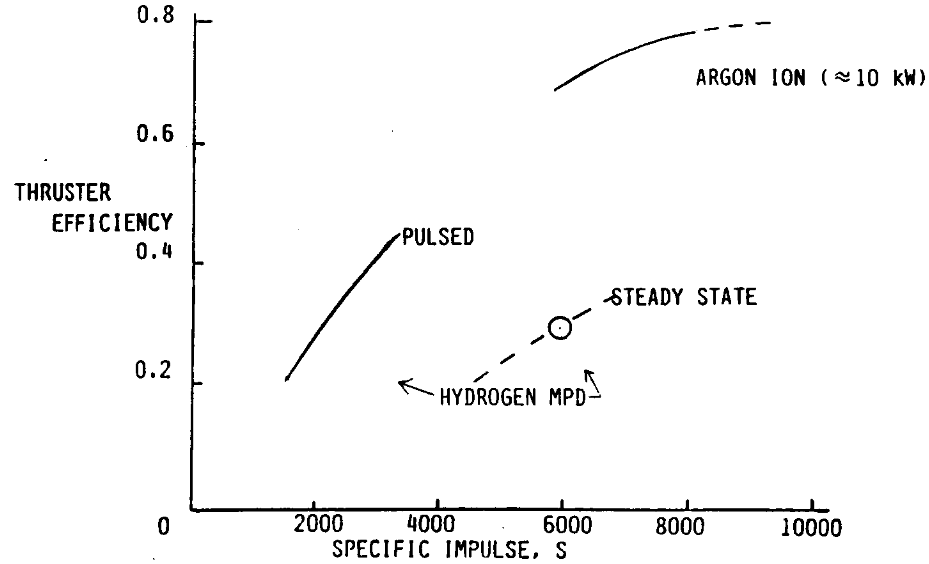
DEMONSTRATED PERFORMANCE



MAJOR TECHNICAL ISSUES:

SCALING ION THRUSTERS; IMPROVED MPD THRUSTER PERFORMANCE

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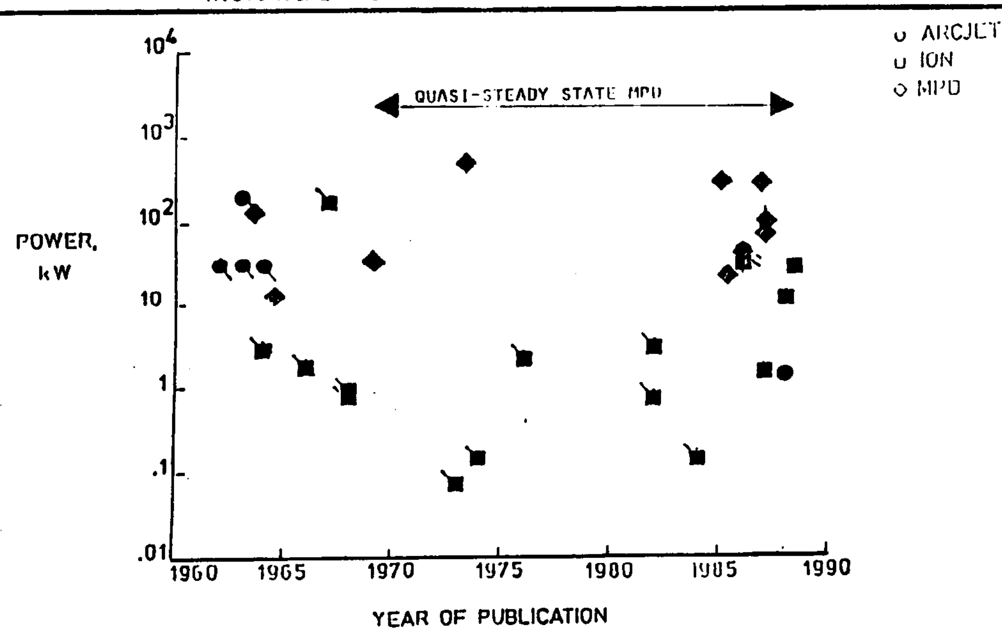
HISTORICAL TREND OF E.P. POWER LEVELS



DEMONSTRATED THRUSTER POWER 10X TO 100X BELOW MW LEVELS

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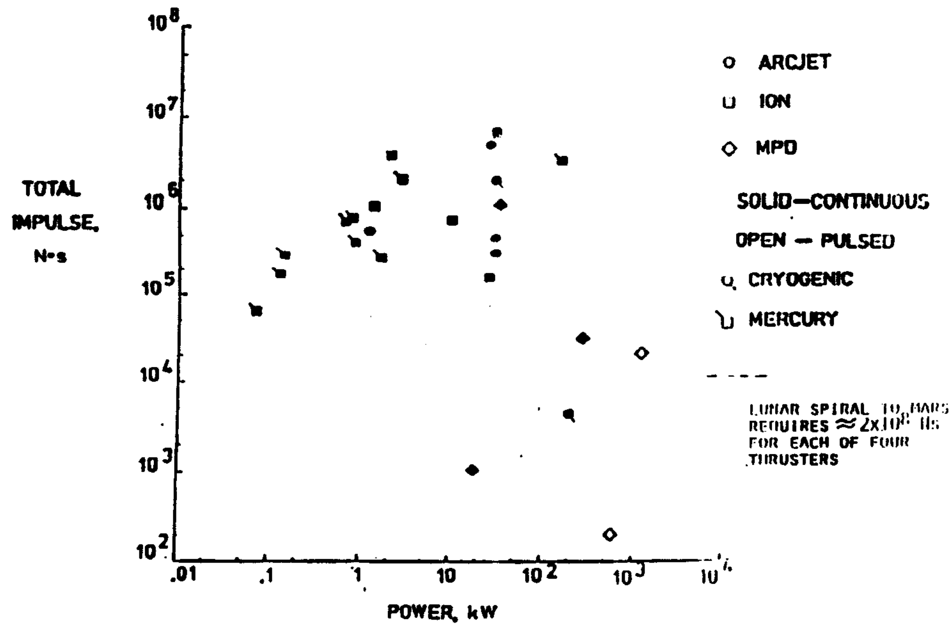
DEMONSTRATED TOTAL IMPULSE FOR ELECTRIC PROPULSION



DEMONSTRATED TOTAL IMPULSE IS ABOUT 100X BELOW TARGET

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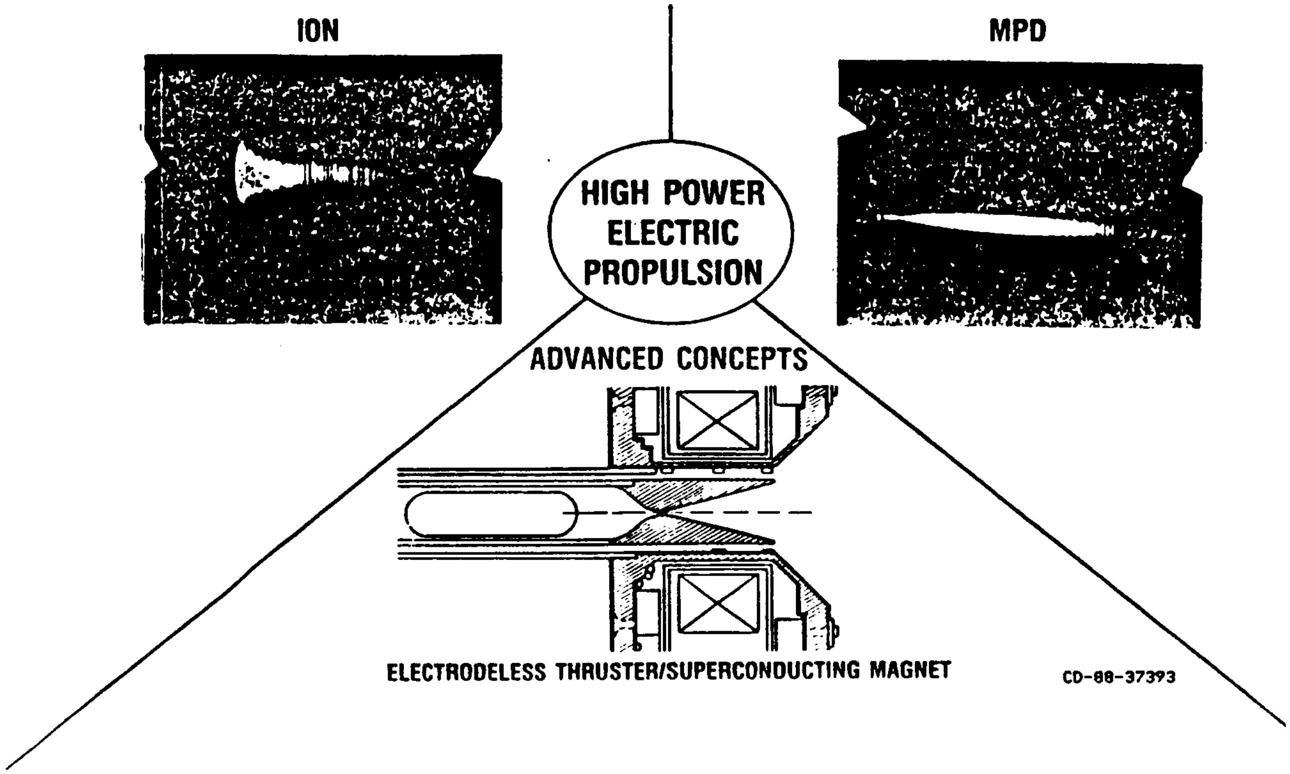
SELECTED CONCEPTS

CONCEPTS	RATIONALE
• ION THRUSTER	• HIGH EFFICIENCY HIGH SPECIFIC IMPULSE
• MPD THRUSTER	• HIGH POWER AND THRUST DENSITY HIGH SPECIFIC IMPULSE

LOW THRUST PRIMARY AND AUXILIARY PROPULSION



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HIGH POWER ELECTRIC PROPULSION

- STATUS SUMMARY -

- DEMONSTRATED PERFORMANCE

	POWER	PERFORMANCE	LIFE
ION	10 TO 25KW XE, AR	I_{SP} = 7000 S η = 0.77 AR	7×10^5 NS XE
MPD	200 KW AR	I_{SP} = 3600 S η = 0.45 H_2, PULSED	1×10^6 NS NH_3

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HIGH POWER ELECTRIC PROPULSION

- STATUS SUMMARY (CONT.) -

- SPACE TESTS

  ION: SERTI, SERT II, ATS6, ETSIII,

  POWER LEVELS $<$ 1KW

  MPD: SEPAC

  PULSED POWER: $\approx$ 2MW, 1MS

- ONGOING TECHNOLOGY PROGRAMS
  - NASA
  - AF
  - SDIO

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ION PROPULSION

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TECHNOLOGY STATUS

- ION PROPULSION -

THRUSTER

- CONFIGURATION
- PERFORMANCE
- TECHNOLOGY TARGETS FOR CARGO VEHICLE PROPULSION
- SCALING

SYSTEM

- THRUST MODULE
- SPACE FLIGHTS
- SEPS DEMONSTRATION
- POWER PROCESSING
- THERMAL
- PROPELLANT STORAGE AND FEED

SUMMARY

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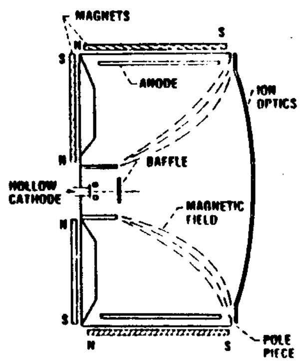
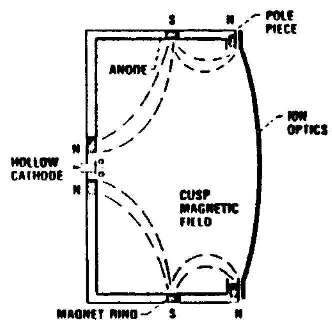
LOW THRUST PRIMARY AND AUXILIARY PROPULSION ION
BASIC THRUSTER DESIGNS

DIVERGENT FIELD



- VOLUME $\vec{B}$
- BAFFLE FOR DISCHARGE IMPEDANCE CONTROL
- USED FOR SERT I, SERT II, IAPS, AND SEPS

RING CUSP



- BOUNDARY MAGNETIC FIELD
- NO BAFFLE

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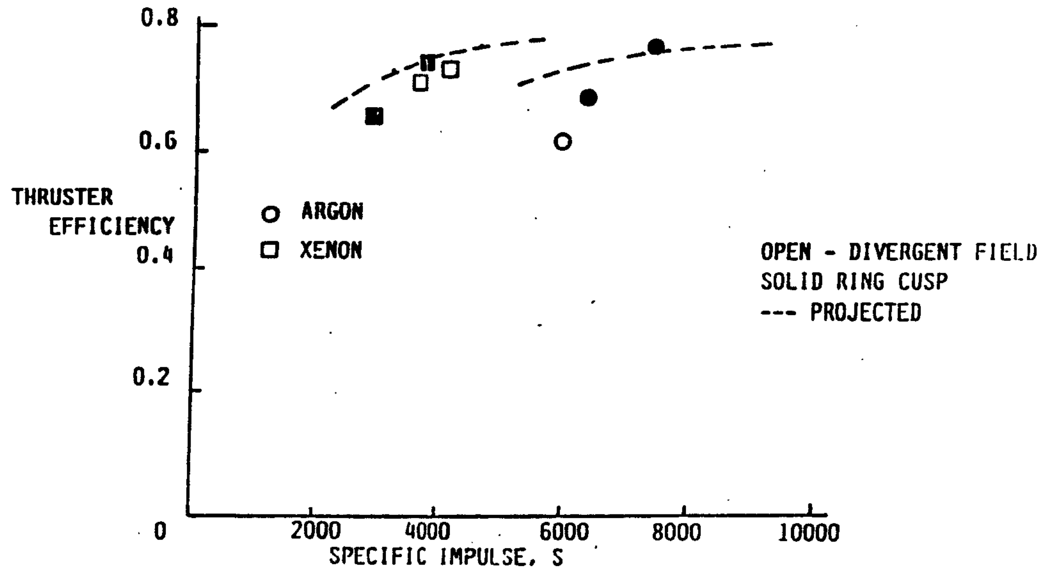
INERT GAS ION PERFORMANCE



THRUSTER EFFICIENCY IS FIXED BY PROPELLANT TYPE AND SPECIFIC IMPULSE

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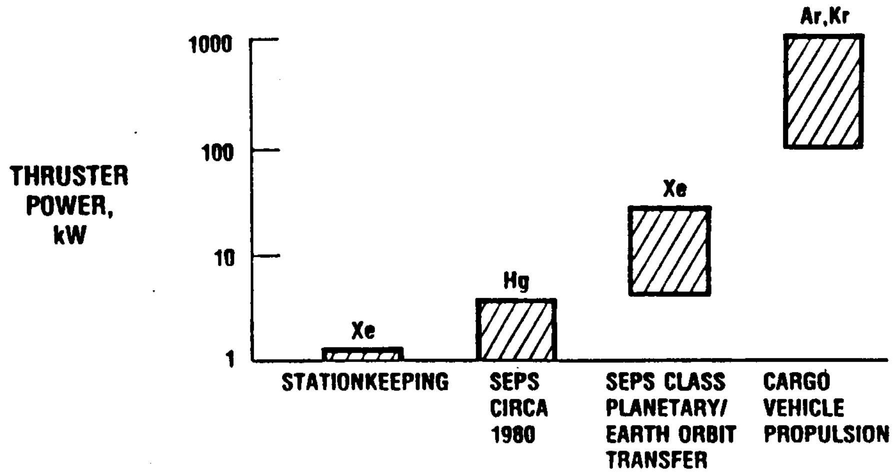
TYPICAL TECHNOLOGY TARGETS

- CARGO VEHICLE ION PROPULSION -

	SOA	LUNAR	MARS
• TOTAL POWER, MW		0.3	4
• DRY SPECIFIC MASS EXCLUDING TANKAGE, KG/KW		< 10	< 10
• PROPELLANT	XENON	ARGON	ARGON
• POWER/ION THRUSTER, MW	0.02	0.1	1
• SPECIFIC IMPULSE, S	4600	8800	8800
• THRUST, N	0.65	1.6	16
• ION OPTICS DIMS, M	0.5 DIA	0.5 DIA	1x1.6
• BEAM VOLTAGE, V	2100	2250	2250
• BEAM CURRENT, A	8.8	40	400
• DISCHARGE CURRENT, A	49	180	1800

LOW THRUST PRIMARY AND AUXILIARY PROPULSION ION
ION TECHNOLOGY/MISSION MATRIX



- NEAR TERM PLANETARY/EARTH ORBIT MISSION TARGET ≈ 5 TO 30 kW/THRUSTER, Xe
- PATHFINDER CARGO MISSION TARGET ≈ 0.1 TO 1 MW/THRUSTER, Ar OR Kr

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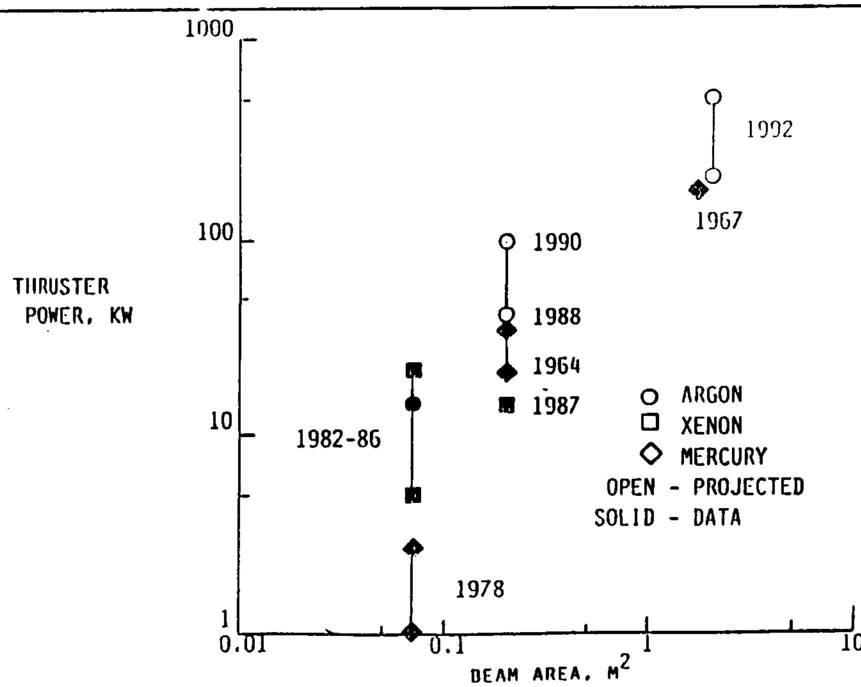
ION THRUSTER SCALING



TECHNOLOGY DRIVER IS ION OPTICS

ION THRUSTER SCALING

RELATIVE SIZE	POWER LEVEL, KW DESIGN/PROJECTED	PROPELLANT	YEAR	DEMONSTRATED
←1.5 M→	270	HG	1966	170 (1967)
	3	HG	1978	9 HG (1980) 21 XE (1986) 14 AR (1987)
	30 30	HG INERT GASES	1963 1986	33 HG (1964) 14 XE (1988) - AR IN TEST
	10 20	XE AR	1988 IN FAB.	
	500	AR	1992	

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GROUND TESTING

- LERC VACUUM FACILITY CAPABILITY
- POTENTIAL LIFE-LIMITING EROSION MECHANISMS
- EFFECT OF VACUUM FACILITY BACKGROUND PRESSURE ON EROSION RATES

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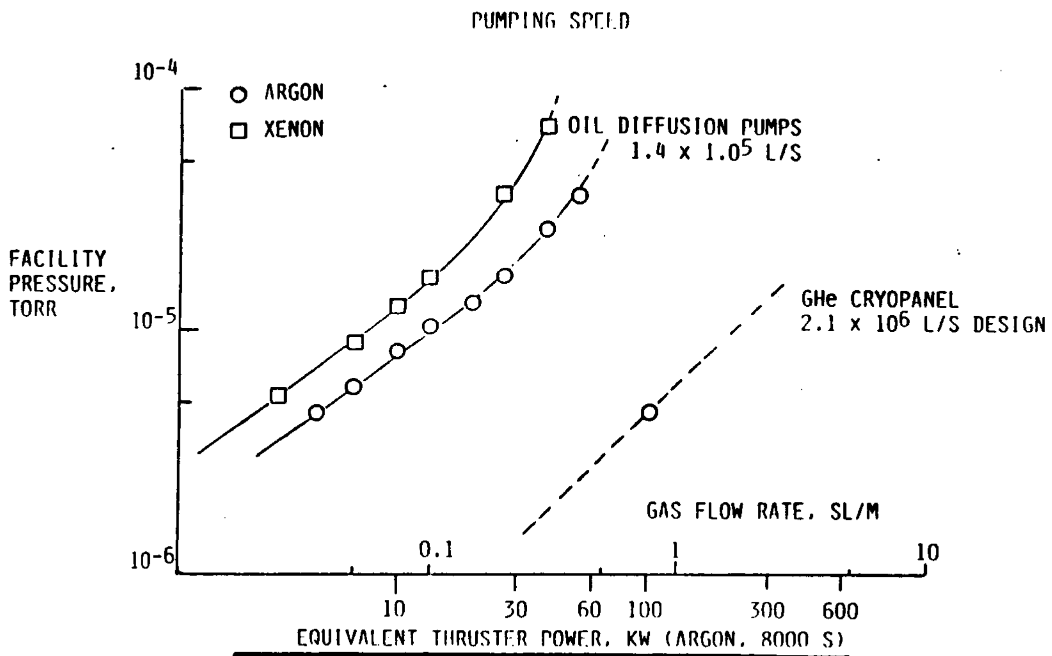
VACUUM FACILITY REQUIREMENTS



He CRYOPANEL REQUIRED FOR P > 60 KW

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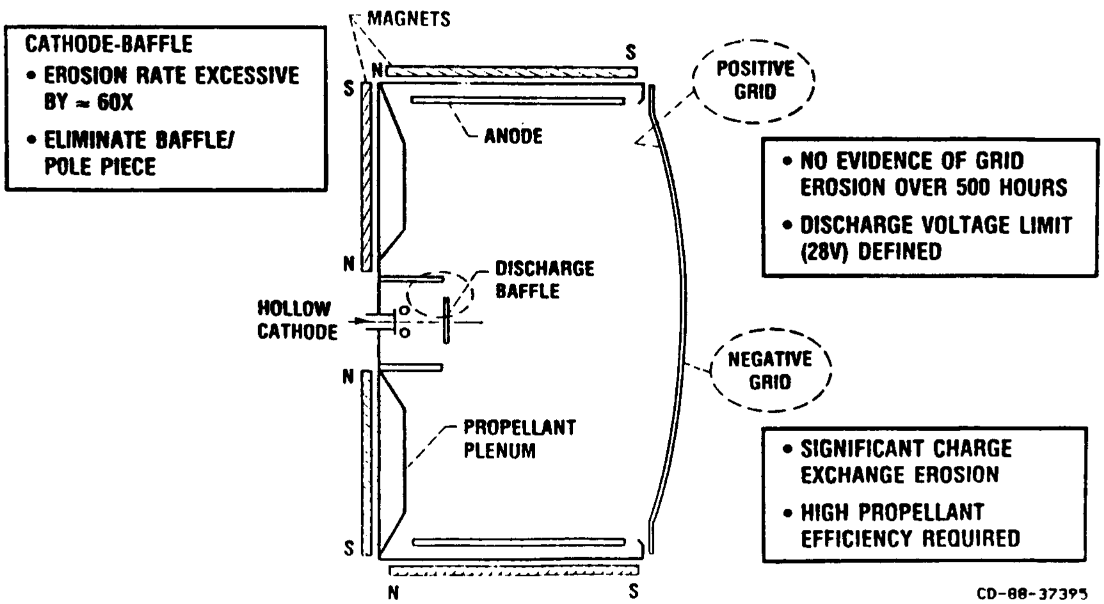
LOW THRUST PRIMARY AND AUXILIARY PROPULSION ION
10 kW THRUSTER LIFE TEST RESULTS



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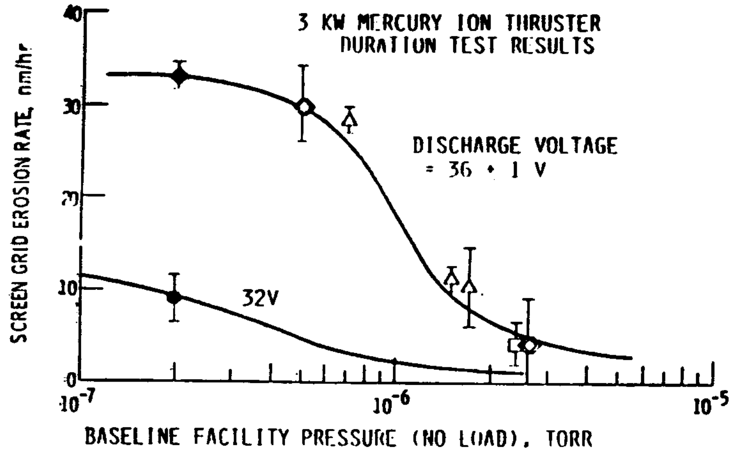
VACUUM FACILITY REQUIREMENTS

CHEMISORPTION OF BACKGROUND GASES
REDUCES MEASURED EROSION RATES



FACILITY BACKGROUND CONSTITUENTS MUST
BE IDENTIFIED AND QUANTIFIED

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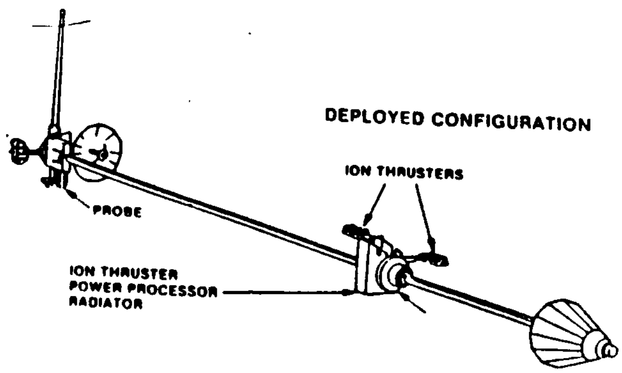
VACUUM FACILITY REQUIREMENTS

- PUMPING SPEED
  - OIL DIFFUSION PUMPS ADEQUATE TO 60 KW
  - GHE CRYOPUMP ADEQUATE TO ABOUT 1 MW
- RESIDUAL GASES
  - CHEMISORPTION OF FACILITY BACKGROUND GASES CAN SIGNIFICANTLY AFFECT WEAR RATES
- BECAUSE OF FACILITY LIMITATIONS IT IS NECESSARY TO DEVELOP RAPID, IN-SITU LIFE DIAGNOSTICS

THRUST MODULE AND SYSTEM IMPACTS

Mars Mission Cargo Vehicle



o NUCLEAR-ELECTRIC PROPULSION

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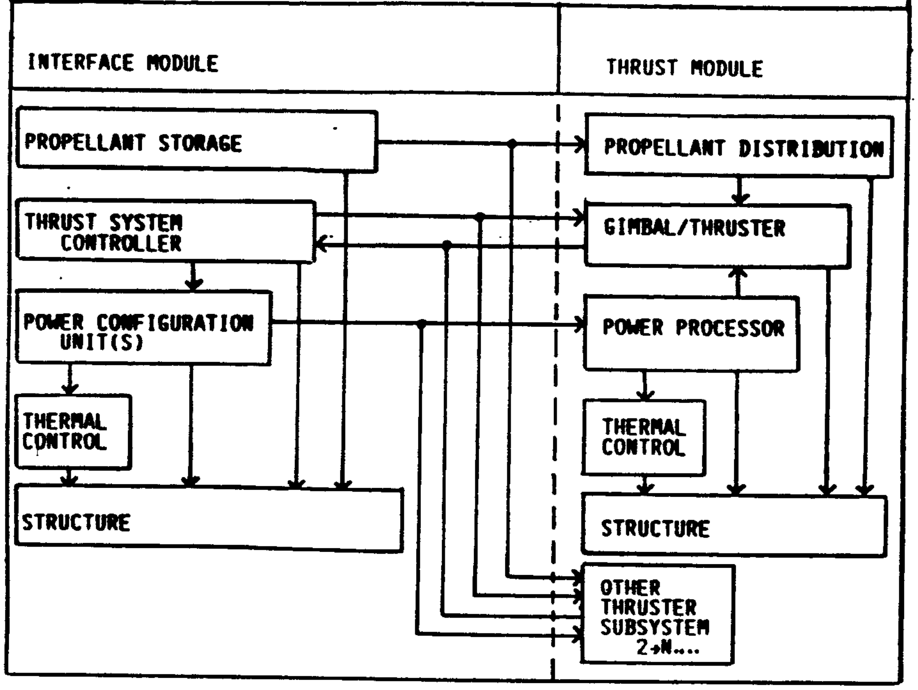
ION PROPULSION THRUST SYSTEM



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SYSTEM IMPACTS RESULTING FROM NEP

SOURCE:	REACTOR	THRUSTER/POWER PROCESSOR	SPACECRAFT
INTERACTIONS:	● RADIATION AND THERMAL EFFECTS ON: - ELECTRONIC POWER COMPONENTS - MAGNETICS - ELECTRIC INSULATION - DIELECTRICS ● POWER BUS	● PLUME EFFECTS - SURFACE MODIFICATION OF CRITICAL SURFACES - THERMAL - COMMUNICATION SIGNAL ATTENUATION ● RADIATED EMI ● THERMAL MANAGEMENT	● INTERACTIONS STRONGLY DEPENDENT ON OVERALL SPACECRAFT DESIGN

THRUST MODULE

- FLIGHT SYSTEM DEMONSTRATIONS

ION PROPULSION

PROGRAM STATUS

O FIVE LOW POWER FLIGHT TESTS PERFORMED AND THREE PLANNED

- SPACE ELECTRIC ROCKET TEST I	1964/NASA
- SNAP 10A	1965/USAF
- SERT II	1970/NASA
- ATS 6	1974/NASA
- ENGINEERING TEST SATELLITE III	1982/JAPAN
- ETS VI	1989/JAPAN
- EUREKA	TBD/WEST GERMANY
- ION AUXILIARY PROPULSION SYSTEM	USAF - TEAL RUBY (CANCELLED)

O HI POWER ION PROGRAMS INITIATED AT LOW LEVEL
  - SYSTEMS ANALYSES (SDIO/SBIR, AFSD, AND NASA)
  - INERT GAS THRUSTER TECHNOLOGY (NASA/OAST)

O POTENTIAL MEGAWATT CLASS PROGRAM SPONSORSHIP UNDER NASA PATHFINDER INITIATIVE

National Aeronautics and Space Administration

Lewis Research Center

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U.S. ION PROPULSION FLIGHT PROGRAMS

MISSION	DESCRIPTION	RESULTS
O SERT I	O 10CM Hg THRUSTER O BALLISTIC TRAJECTORY	O VERIFIED —BEAM NEUTRALIZATION —THRUST
O SERT II	O 15CM Hg THRUSTERS O 1000 KM POLAR ORBIT	O LONG TERM COMPATIBILITY DEMO. —SPACECRAFT SYSTEMS —GEOCENTRIC ENVIRONMENT O THRUST LEVEL CONFIRMED O ZERO G PROBLEM EXPOSED AND RECTIFIED
O ATS 6	O 10CM CS THRUSTER O GEOSYNCHRONOUS	O DEMONSTRATED —S/C POTENTIAL CONTROL —S/C THRUST SYSTEM COMPATIBILITY

ATI

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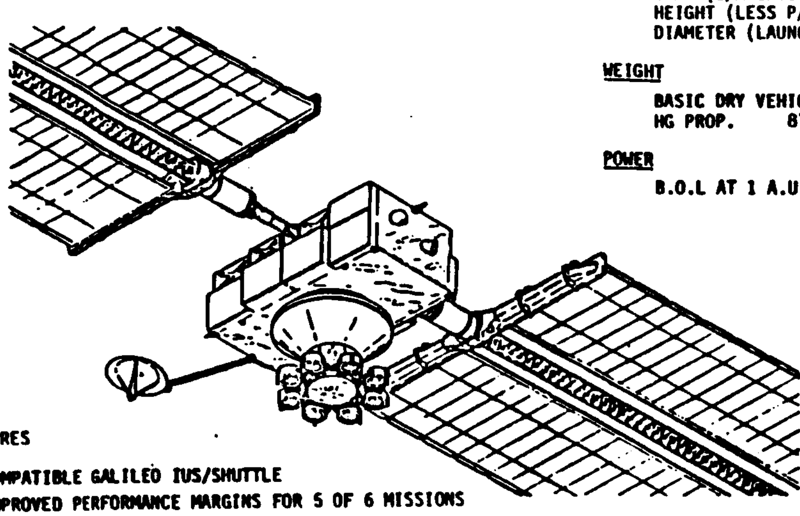
BACKGROUND

SUMMARY OF FLIGHT TEST PROGRAMS

- VERIFIED GROUND TEST RESULTS
  - THRUST LEVEL AND DIRECTION
  - PLUME CHARACTERISTICS
  - THRUSTER MATERIAL EFFLUX
- REVEALED AND RESOLVED ZERO "G" PHENOMENA
  - SPUTTERED MATERIAL DEPOSITS
  - ACCELERATOR GRID EROSION BY NEUTRALIZER IONS
- DEMONSTRATED SV POTENTIAL CONTROL
- CONFIRMED SV/THRUST SYSTEM COMPATIBILITY
  - EMI
  - COMMUNICATIONS
  - THERMAL SYSTEM
  - SV/EARTH ORBIT ENVIRONMENT
- DEMONSTRATED LONG TERM GROUND AND SPACE STORAGE CAPABILITIES
- DEMONSTRATED AUTONOMOUS CONTROL
  - NOVA (μ LB)
  - SERT II (m LB)



SIZE

SPAN (S/A EXTENDED)	67 M
HEIGHT (LESS P/L)	2.58 M
DIAMETER (LAUNCH)	4.42 M

WEIGHT

BASIC DRY VEHICLE	1483 KG
HG PROP.	819 to 2456 KG

POWER

B.O.L AT 1 A.U.	31.176 KW

FEATURES

- COMPATIBLE GALILEO IUS/SHUTTLE
- IMPROVED PERFORMANCE MARGINS FOR 5 OF 6 MISSIONS
- UNITIZED PROPULSION SUB-MODULE
- VERSATILE PAYLOAD ACCOMMODATIONS

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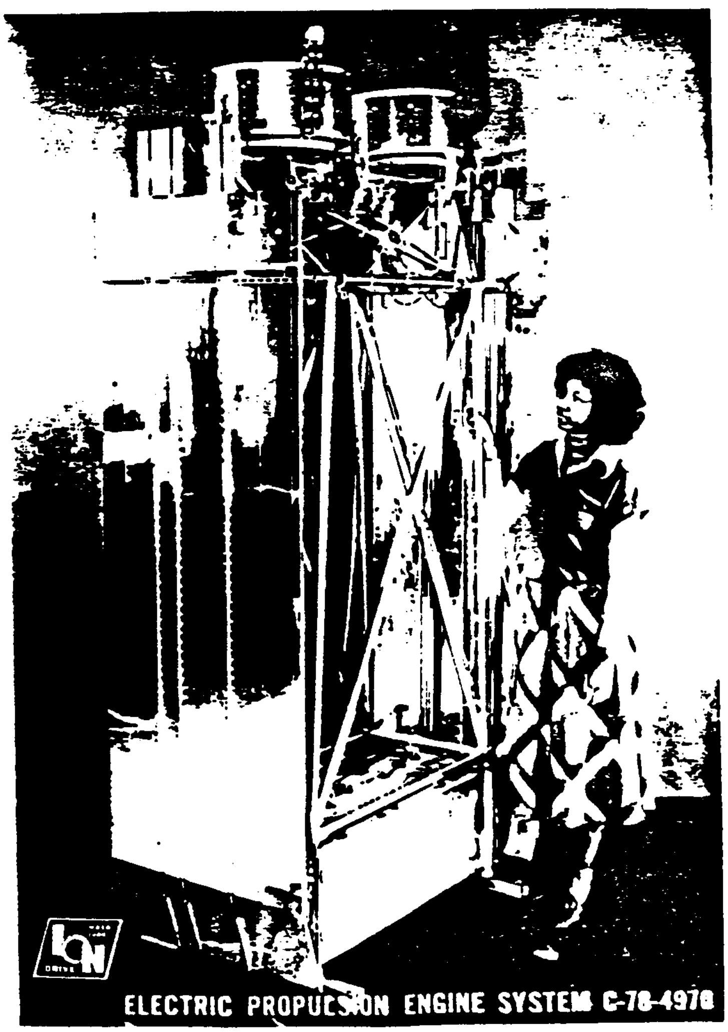

SEPS BIMOD

BACKGROUND

SEPS - SOLAR ELECTRIC PROPULSION STAGE

SUMMARY OF RESULTS

- SIGNIFICANT PROGRAM INVESTMENT
  - 30 MILLION DOLLARS
  - 10 YEAR PERIOD
  - MULTICENTER/CONTRACTOR
- NUMEROUS SPACE VEHICLE DESIGNS/STRATEGIES
  - PLANETARY
  - NEAR EARTH
- ALL CRITICAL SV ELEMENTS DEVELOPED TO ADVANCED STATUS
  - LARGE 25 KW SOLAR ARRAYS (15 KG/KW)
  - POWER PROCESSORS (12 KG/KW)
  - THERMAL CONTROL (HEAT PIPES)
  - GIMBALS
  - THROTTLEABLE, LONG LIFE ION THRUSTERS (30 CM)
  - PROPELLANT STORAGE AND DISTRIBUTION (HG)
- THRUST SYSTEM TECHNOLOGY TRANSFERRED
  - NASA FLIGHT CENTERS
  - INDUSTRY
- TECHNOLOGY SHELVED

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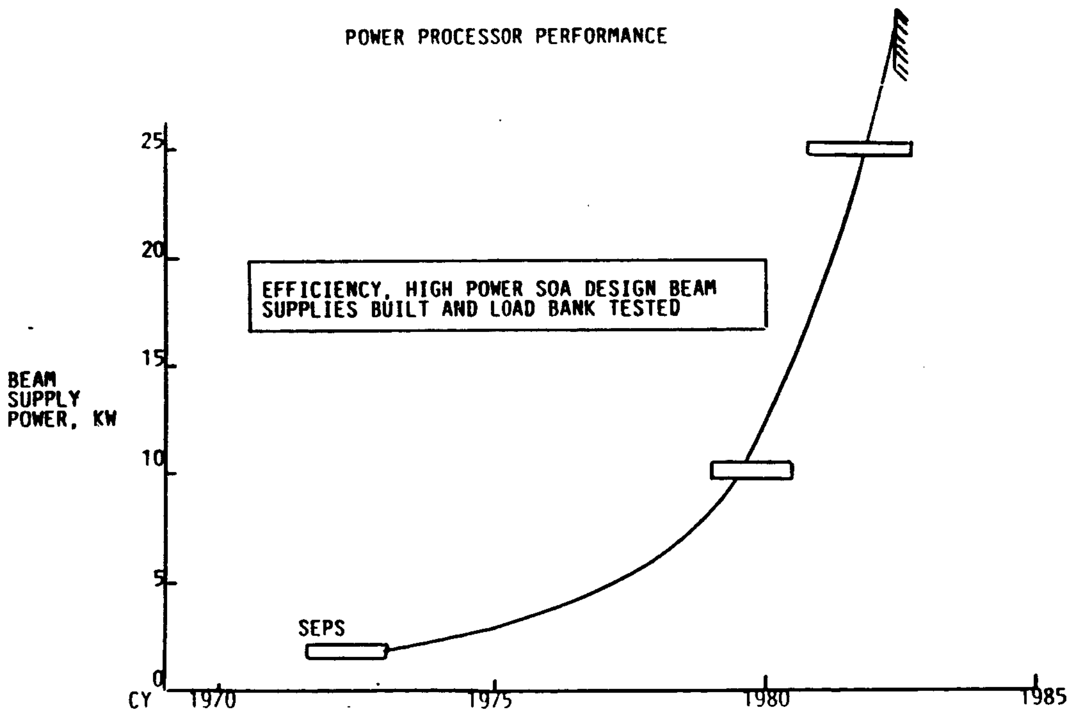
STATUS

POWER PROCESSOR PERFORMANCE



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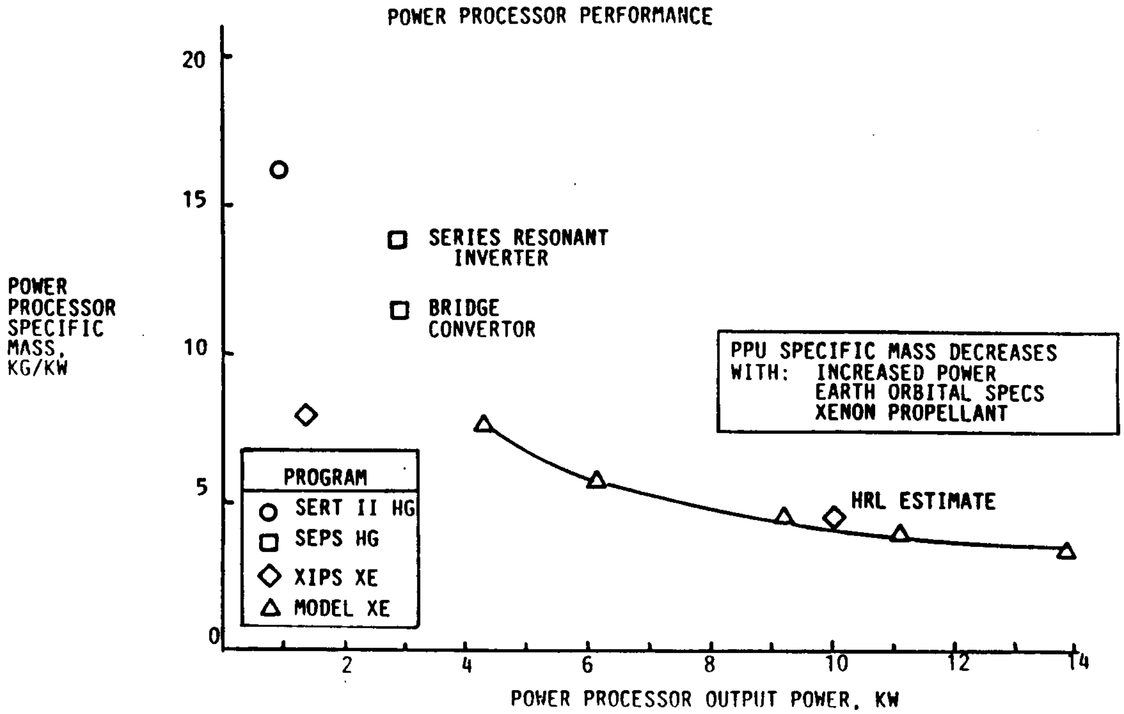
STATUS



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STATUS

POWER PROCESSOR SUMMARY

- XIPS, 1.3 KW PPU
  - SUCCESSFULLY DEMONSTRATED 4350 HR; 3850 CYCLES
  - 8 KG/KW
- BEAM POWER SUPPLIES 10 AND 25 KW FABRICATED
  - NOT TESTED WITH THRUSTER
- SPECIFIC MASS< 5 KG/KW PREDICTED FOR PPU

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STATUS

THERMAL CONTROL

- REQUIRED BY POWER PROCESSOR AND INTERFACE MODULE
- THRUSTER IS SELF-RADIATING
  - MAJOR PORTION OF POWER IN BEAM
- HEAT PIPES AND RADIATORS DEVELOPED FOR LOW POWER SYSTEMS
  - FLIGHT QUALIFIED ON CTS
  - FLIGHT DESIGNS FOR SEPS, EPSEP

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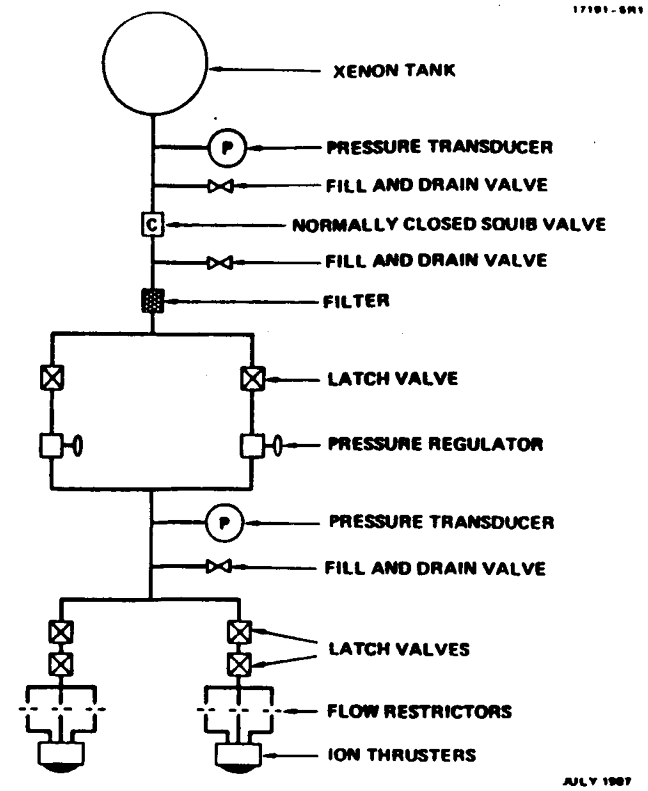
STATUS

PROPELLANT STORAGE AND DISTRIBUTION (ARGON, KRYPTON)

- HIGH PRESSURE GAS STORAGE 1100-4200 PSIA
  - SMALL TANKS FLIGHT QUALIFIED
- ARGON CRYOGENIC STORAGE NEEDS TO BE DEVELOPED
- PRESSURE REGULATOR, TO 10 PSIA
  - MODIFIED MARS-VIKING DESIGN
  - TESTED FOR 4350 HOURS
- ALL FLOW DISTRIBUTION COMPONENTS FLIGHT QUALIFIED EXCEPT GAS FLOW IMPEDANCES

HUGHES

PROPELLANT TANKAGE AND FLOW CONTROL UNIT



ALL COMPONENTS FLIGHT QUALIFIED EXEPT GAS FLOW IMPEDANCES

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SUMMARY -- ION PROPULSION

- GOALS FOR CARGO VEHICLE PROPULSION IDENTIFIED
- THRUSTER AND POWER PROCESSING MUST BE SCALED BY A FACTOR OF 50 FOR MEGAWATT CLASS DEVICES
- ION OPTICS SCALING IS THE KEY THRUSTER TECHNOLOGY
- DEMONSTRATED TOTAL IMPULSE > 50X BELOW MARS CARGO VEHICLE PROPULSION TARGET
- LARGE HELIUM CRYOPUMPS ARE REQUIRED FOR GROUND TESTS WITH P > 60 KW
- SYSTEM INTERFACES, INTEGRATION AND FLIGHT QUALIFICATION FOR MEGAWATT SYSTEMS NEED FURTHER STUDY

JPL

CARGO VEHICLE PROPULSION

MPD STATUS

Dr. David Q. King
Supervisor, Electric Propulsion and
Plasma Technology Group
Jet Propulsion Laboratory
Pasadena, California
February 8, 1989

DQK:1

JPL

Foreign Activities

JAPAN

ION

- **Mitsubishi is selling a complete system for station keeping**

ARCJET

- **University research on several configurations**

MPD

- **Largest program**
  - High Quality, diverse university, industry, and government research program
- **SEPAC - shuttle test in 1984**
- **1 kW Pulsed MPD free flyer - 88 or 89 launch on H1 - recovered by shuttle**

DQK:1

JPL

Foreign Activities

West GERMANY

ION

- U. Giessen, MBB/ERNO
- RIT 10 - 10 cm, 0.5 kW, Xenon
  - System will be tested on EURECA 1
  - Hardware qualified & delivered by 12/87
- RIT-35 - 35 cm, 7-11 kW, Hg, 4200-4700 Sec.
  - R&D effort to support CNSR
  - Collaboration with RAE in U.K.

ARCJET

- U. Stuttgart
- 15 kW
- Competition for US SP-100 reference mission

DQK:2

JPL

Foreign Activities

West GERMANY

MPD

- U. Stuttgart
- 100-400 kW Steady-State devices running since 1970's
  - 1000-3000 s I_{sp}, 15-22% Thrust Efficiency
  - Also studying pulsed, quasi-steady devices
- Basic research funded by AFOSR, matched by university

MISSION STUDIES

- U. Munich

DQK:3

JPL **Foreign Activities**

UNITED KINGDOM

ION

- **UK-10, Royal Aerospace Establishment, Culham Laboratories**
  - 10 cm, 0.3-0.9 kW, Xenon, 3400-3600 Sec.
  - Demonstration of station keeping fligh planned for 1991
- **UK-25, RAE, Culham Laboratories**
  - 25 cm, 5-7.5 kW, approx. 4500 sec.
  - Under Development in Collaboration with MBB
  - Objective is to support ESA CNSR

DQK:4

JPL **Foreign Activities**

ITALY

MPD

- **U. Pisa, U. Rome, SNIA-BPD**
  - Pulsed, quasi-steady system

ARCJET

- **Subcontracted to U. Stuttgart**
- **Objective is 15 kW for Orbit Rasing**

FEEP

- **U. Vienna**
- **Cs propellant, .5 kW**

DQK:5

JPL

Foreign Activities

CHINA

PPT

- Electric Propulsion Laboratory of Space Science and Technology Center
- MDT-2A tested on 37 minute ballistic flight circa 1980
  - 5 watts
  - Space flight planned

ION

- Lanzhou Institute of Physics, Chinese Academy of Space Technology
- Hg, 6 & 12 cm, 'LF-8' was "qualified" in 1968
  - "... not been autorhized to introduce the condemed work being finished there (Lanzhou), so the related contents are omitted." Shi-Ming An, et. al., AIAA-87-1101, May 1987.

DQK:6

JPL

Foreign Activities

USSR

MPD & ARCJET

- Battery operated tests of 10-100 kW MPD/Arcjet in space

Hall Thrusters

- More extensive work on Hall type thrusters (called ION thrusters in USSR) than other types

Miscellaneous

- No publications since 1981
  - Except under Cathode, Anode, & Acceleration Processes
- Private communication of Prof. Zhurin with R. G. Jahn indicates work is ongoing.
- 6th Space Nuclear Power Symposium - Soviet Presentation on NEP Plans

DQK:7

JPL EXPERIMENTAL OBJECTIVES

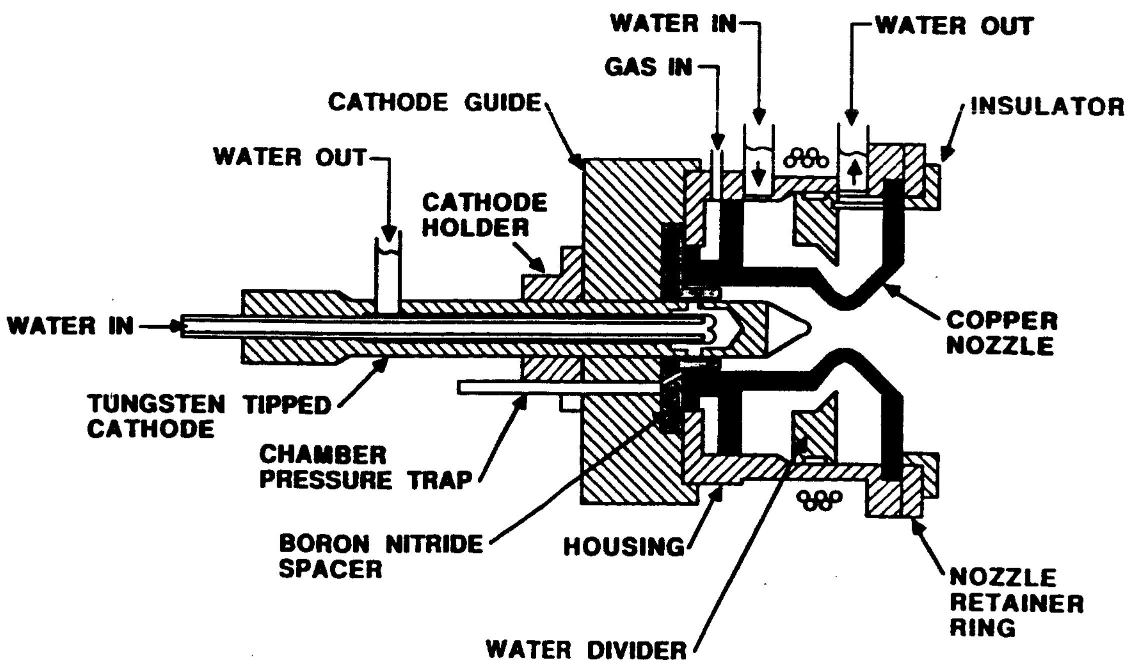
FAR TERM:

TO BUILD A HIGHLY EFFICIENT, HIGH SPECIFIC IMPULSE MULTI-MEGAWATT MPD THRUSTER FOR EARTH ORBITAL AND INTERPLANETARY PROPULSION

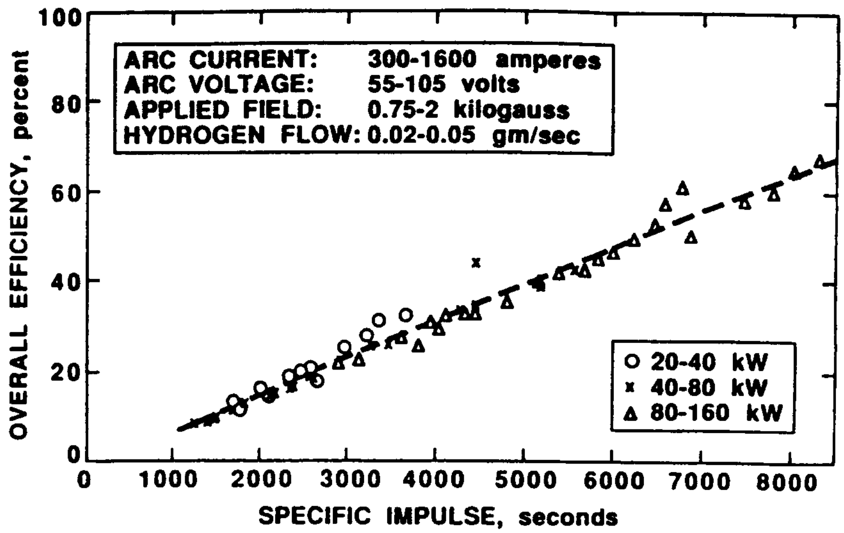
NEAR TERM:

TO DEVELOP UNDERSTANDING OF THE OPERATION OF THE STEADY-STATE MPD THRUSTER AT POWER LEVELS UP TO 250 kW

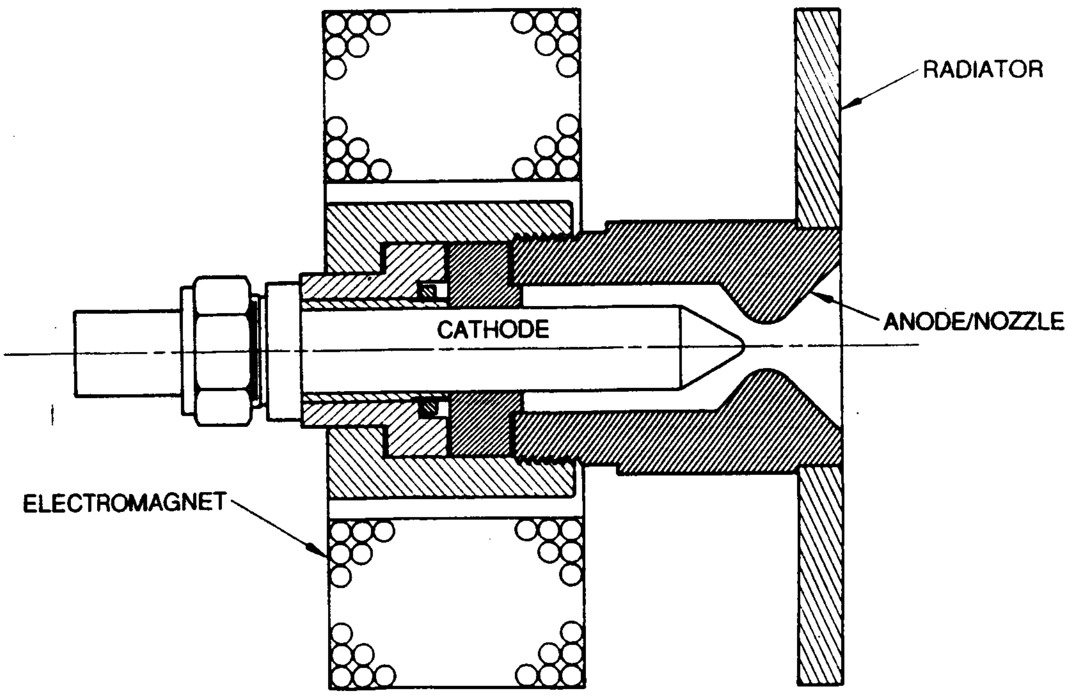
JPL SCHEMATIC OF LIQUID COOLED, APPLIED FIELD, HYBRID ENGINE



THRUST EFFICIENCY vs. SPECIFIC IMPULSE WITH ARC CURRENT AND VOLTAGE, APPLIED MAGNETIC FIELD AND PROPELLANT FLOW RATE AS PARAMETERS

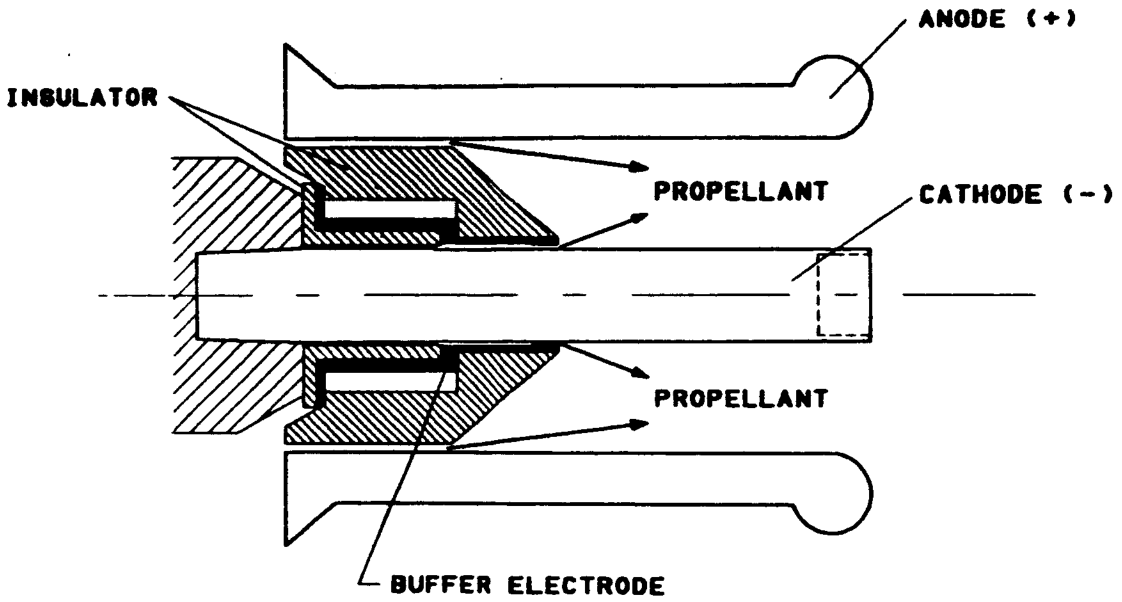


SCHEMATIC OF JPL RADIATION COOLED, APPLIED FIELD, HYBRID ENGINE



JPL

MPD THRUSTER
SIMPLIFIED SCHEMATIC



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MPD THRUSTER OPERATIONAL ACCOMPLISHMENTS

1. 80 RUNS TOTALING 11 HOURS OF OPERATION
   - **Maximum power over 72 kWe at 2245 amps**
   - **System design proven successful**

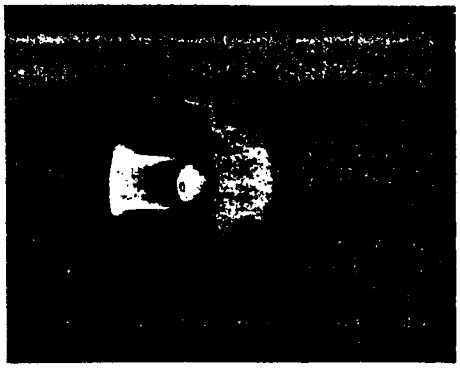
2. ENGINE OPERATED FOR A 1 HOUR 23 MINUTE PERIOD
   - **No arc spot damage on cathode**
   - **Cathode tip temperature was < 1970° C for operation up to 1700 amps, 0.16 g/s argon**

3. FACILITY OPERATION RESUMED IN SEPTEMBER 1988 AFTER MOVE TO A NEW LOCATION

JPL

CURRENT ACTIVITIES: OPERATING MODE

- DISTINCT STEADY-STATE OPERATING MODES OBSERVED BY D. KING IN 1987
- ONE MODE IS CHARACTERIZED BY A LUMINOUS CATHODE JET. A SECOND MODE HAS A COOLER CATHODE TIP AND NO CATHODE JET; THE TERMINAL VOLTAGE IS LOWER.
- SECOND MODE MAY PROVIDE MORE EFFICIENT PLASMA ACCELERATION



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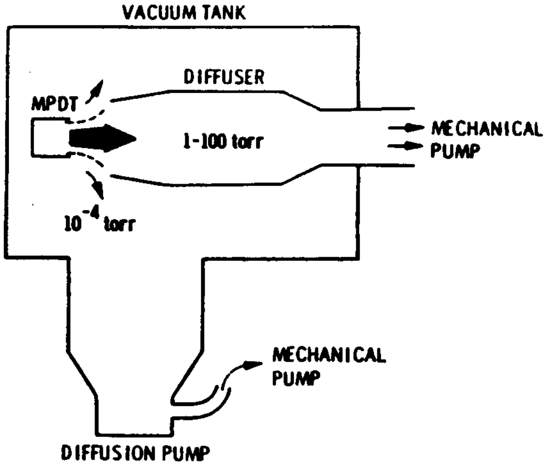
CURRENT ACTIVITIES: DIFFUSER DESIGN

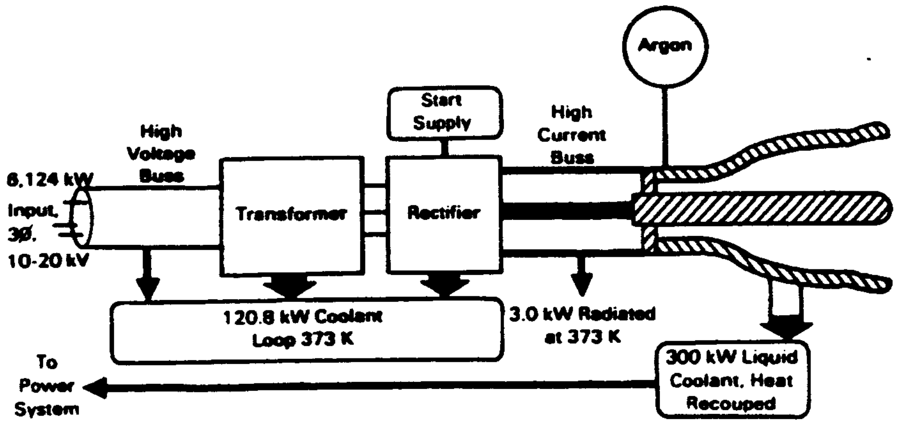
- 10E-4 TORR IS MAXIMUM ACCEPTABLE TANK PRESSURE DURING STEADY-STATE MPD THRUSTER TESTING
- FOR A PROPELLANT FLOW RATE OF 0.4 g/s, EXISTING VACUUM SYSTEM PROVIDES ABOUT 10E-1 TORR
- A GASDYNAMIC DIFFUSER MAY BE USED TO ENHANCE PUMPING CAPABILITY (AS DONE FOR CHEMICAL ROCKET TESTING)



- TECHNICAL ISSUES:
  1) Rarefied flow dynamics in diffuser
  2) Effect of diffuser on arc geometry

MPD PROPULSION SYSTEM ISSUES

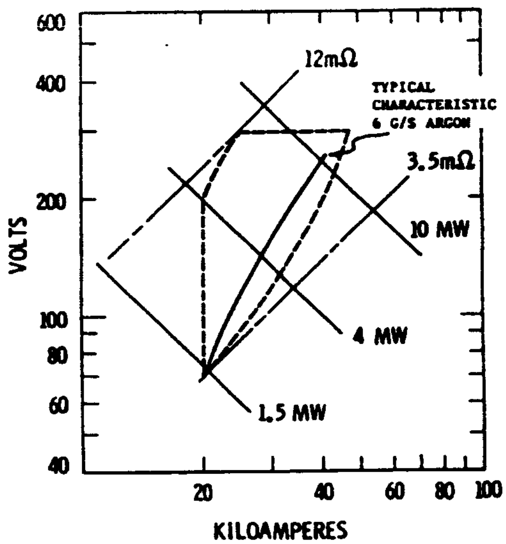
- **CONDUCTIVE PLUME REQUIRES MPD BE VOLTAGE ISOLATED FROM S/C POWER SYSTEM**
- **SIGNIFICANT HEAT LOAD FROM ANODE CAN BE RETURNED TO PRIMARY HEAT LOOP**



DQK:2

Projected Power Requirements for Megawatt MPD Thrusters

- RIPPLE <1% BELOW 500 HZ
- HIGHLY CONDUCTIVE PLUME IMPLIES ISOLATION FROM S/C REQUIRED
- 10-20% OF INPUT POWER REJECTED BY ANODE
  - POSSIBLE RECOVERY TO PRIMARY HEAT LOOP AT HIGH TEMPERATURE



DQK:1

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SUMMARY

FOREIGN ACTIVITIES

EUROPE & JAPAN

- SIGNIFICANT COMPETITION FOR SP-100 PROPULSION AND PLANETARY EXPLORATION

USSR

- OPERATIONAL

MPD PROPULSION

THRUSTER

- PERFORMANCE AND LIFE GOALS IDENTIFIED
- THRUSTER FEASIBILITY BEING EVALUATED
  - KEY ISSUE: **100 FOLD IMPROVEMENT IN LIFE**
  - FACTOR OF 10-20 IN POWER LEVEL (1-10 MW DESIREABLE, 0.5-1.0 MW CONCEPTS POSSIBLE)

DQK:3

JPL

SUMMARY

SYSTEM

- NO RELEVENT SPACE FLIGHT EXPERIENCE IN MW POWER PROCESSING
  - ESTIMATE 1 KG/KW SPECIFIC MASS
- ENGINE IMPACTS ON SYSTEM DESIGN
  - PLUME EFFECTS BOTH THERMAL AND ELECTRICAL
  - THRUSTER HEAT REJECTION

SUMMARY

TESTING

- LOW PRESSURE, HIGH VOLUME & HEAT LOAD
- FACILITY FOR MW TESTING DOES NOT PRESENTLY EXIST
  - VACUUM & THROUGHPUT BELIEVED TO BE 10-4 TORR AT 1-10 G/S, BUT MAY CHANGE WITH FURTHER STUDY

DQK:4

JPL/LOS ALAMOS	SPACE REACTOR POWER SYSTEMS SP-100 PROJECT	

TECHNOLOGY STATUS

PRESENTED

TO

JOINT MEETING ON POWER AND PROPULSION TECHNOLOGIES

FOR

CARGO VEHICLE PROPULSION

AT

NASA HEADQUARTERS

FEDERAL BUILDING 6 RM 5092

WASHINGTON, DC

8 JANUARY 1989

BY JACK F. MONDT

DEPUTY MANAGER

SP-100 PROJECT

JPL/LOS ALAMOS	SP-100 GES PROJECT PROGRAM DEVELOPMENT	

- GOAL OF PROGRAM
  - DEVELOP SPACE REACTOR POWER SYSTEMS (SRPS) TO PROVIDE ELECTRIC POWER FOR A VARIETY OF SPACE MISSIONS
- OBJECTIVES OF GROUND ENGINEERING SYSTEM (GES) PHASE
  - DEMONSTRATE THAT THE TECHNOLOGY IS READY FOR FLIGHT APPLICATION
  - DISSEMINATE PROJECT PLANS AND ACCOMPLISHMENTS TO POTENTIAL USERS AND SUPPORT THEIR MISSION PLANNING

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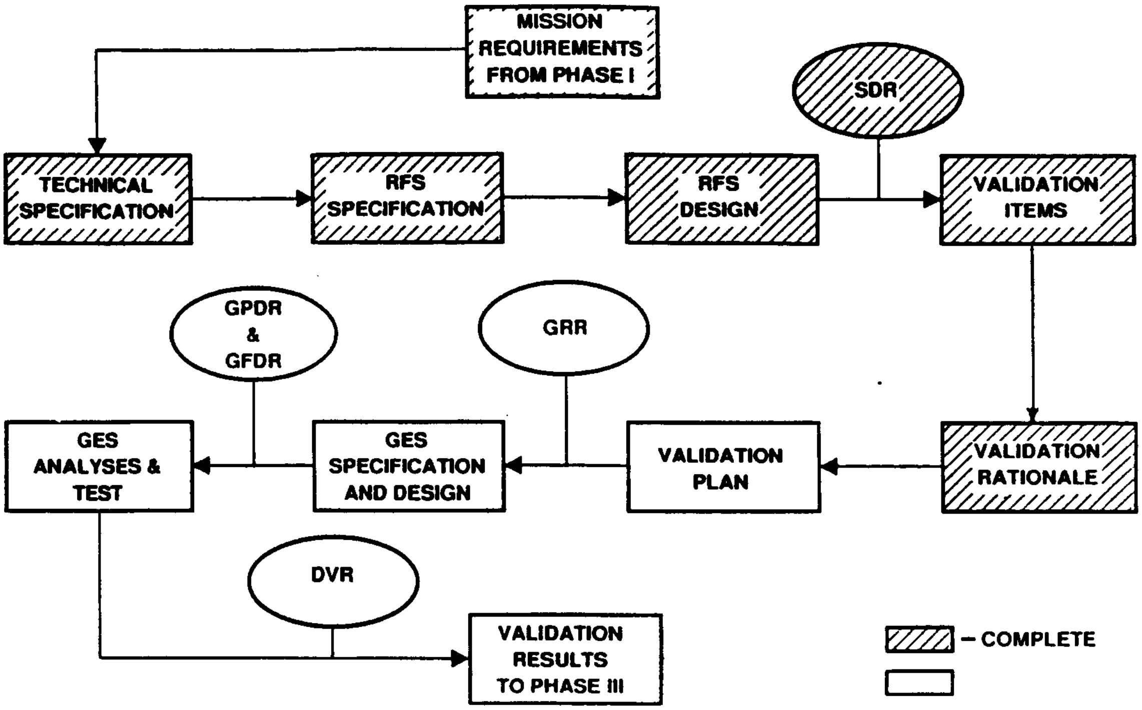
VALIDATION APPROACH SUMMARY



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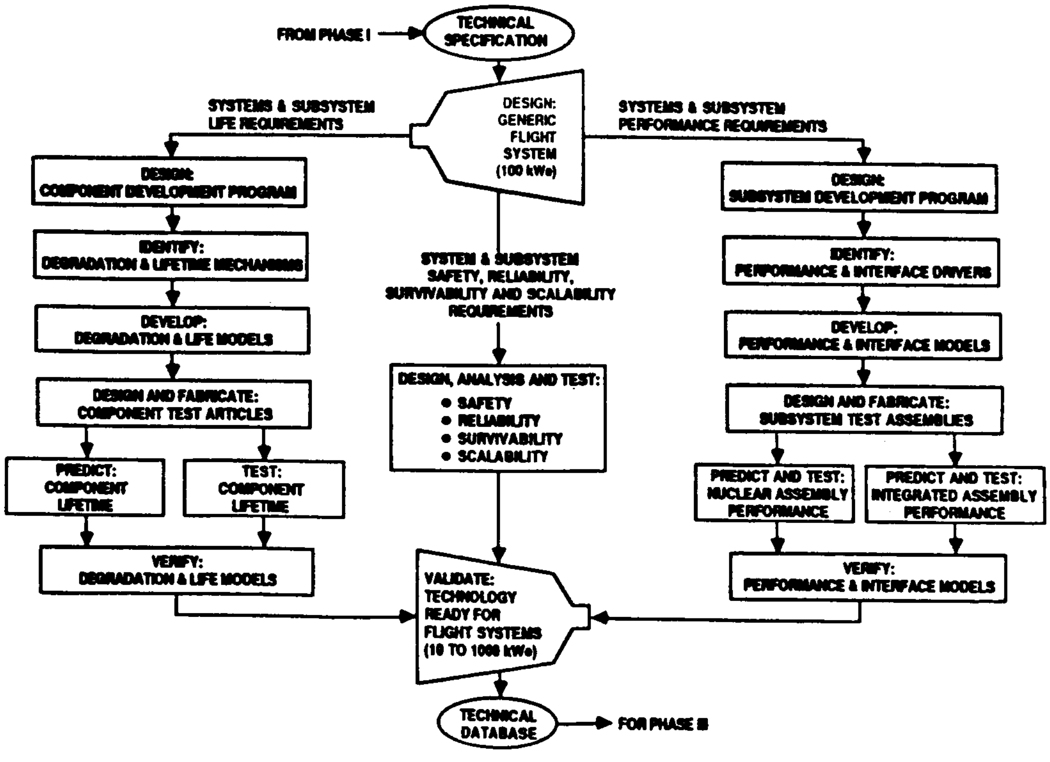
SP-100 GES PHASE II ACTIVITIES



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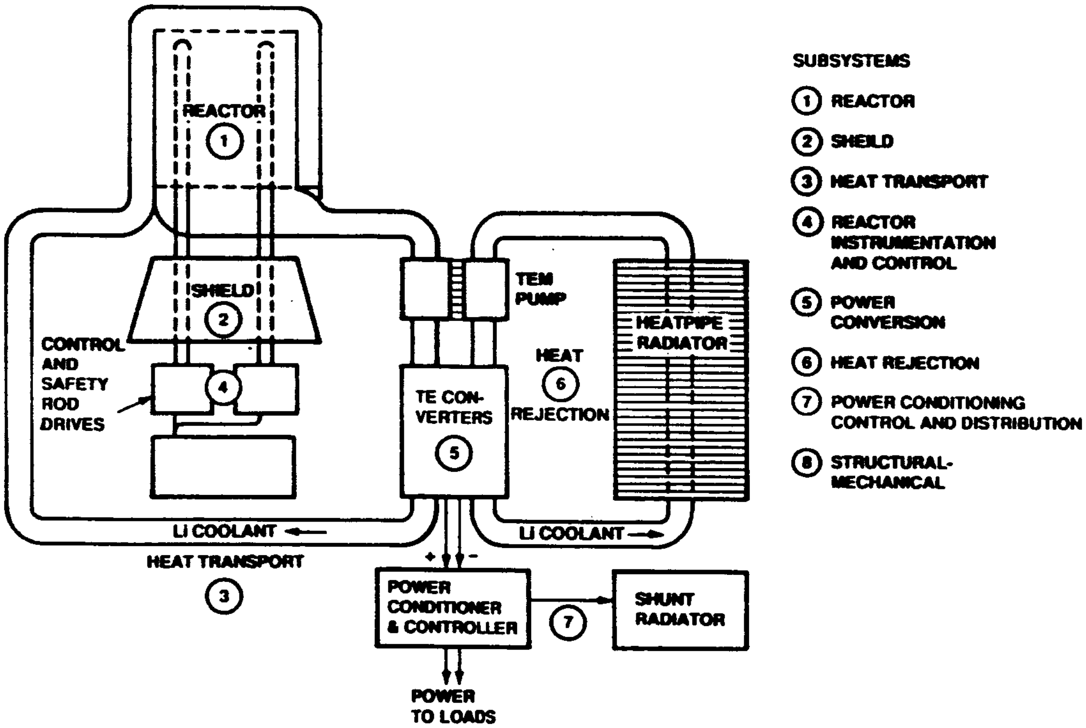
SP-100
POWER SYSTEM SCHEMATIC



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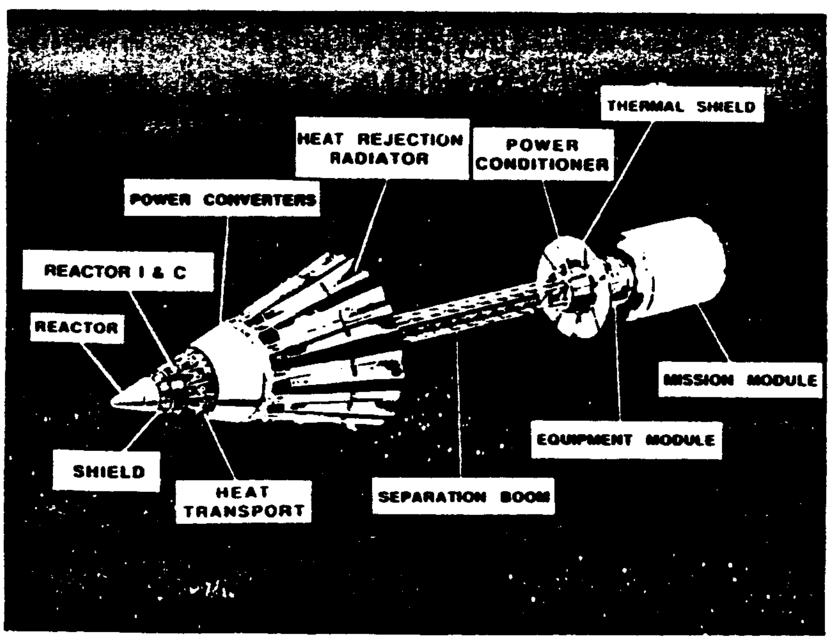
SP-100 GES PROJECT
SP-100 GFS CONFIGURATION



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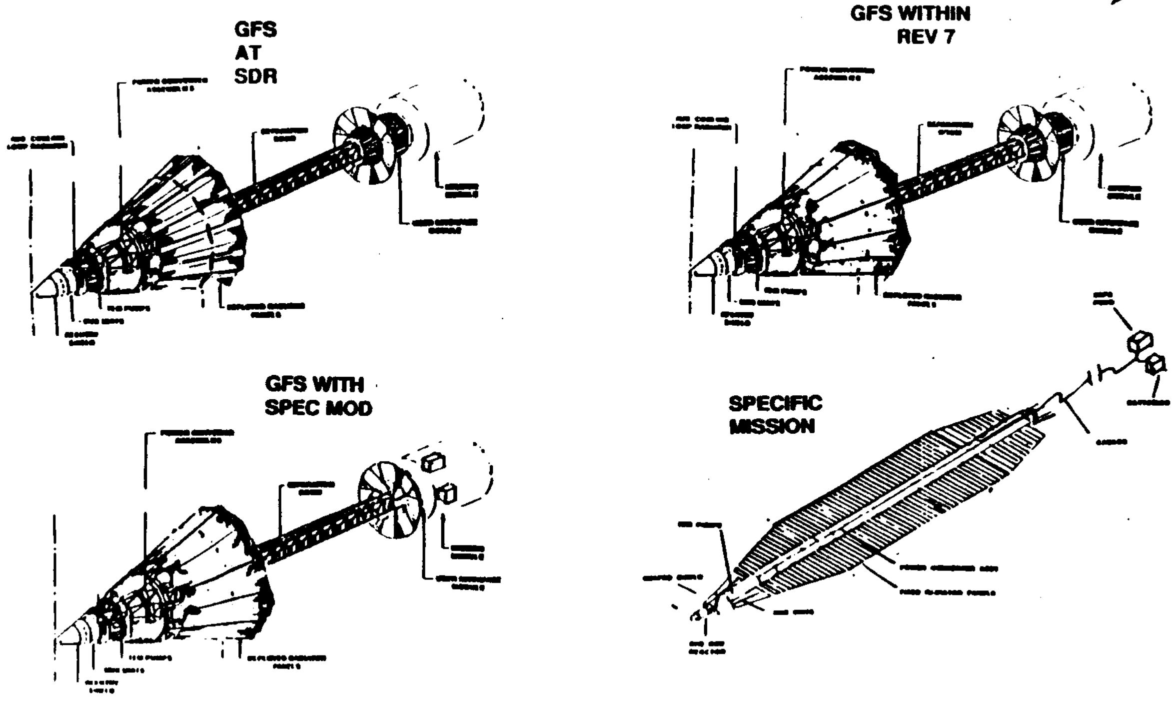
SP-100 MASS MINIMIZATION STUDY RESULTS

	GFS AT SDR	GFS W/IN REV 7	GFS WITH SPEC MOD	SPECIFIC MISSION
REACTOR	803	775	640	635
SHIELD	1,255	920	860	585
PRIMARY HEAT TRANSPORT	632	470	445	365
REACTOR I&C	359	345	210	230
POWER CONVERSION	409	320	315	385
HEAT REJECTION	1,027	880	835	655
POWER CC&D	399	375	200	310
MECHANICAL/STRUCTURAL	538	375	285	450
TOTAL SYSTEM	5,422	4,460	3,790	3,615

NOTE: MASS VALUES ARE EXPRESSED IN KILOGRAMS

SYSTEM CONFIGURATIONS



SYSTEM CHARACTERISTICS

	GFS AT SDR	GFS W/IN REV 7	GFS WITH SPEC MOD	SPECIFIC MISSION
SYSTEM POWER LEVEL (kWe)	100	100	100	100
HOUSEKEEPING POWER (W)	300	300	300	300
ORBIT LIFE (YRS/YRS FULL POWER)	10/7	10/7	7/7	7/7
ORBIT ALTITUDE (KM)	N/A	N/A	1100	1100
ORBIT ORIENTATION	N/A	N/A	N/A	EDGE ON
LAUNCH VEHICLE	STS	STS	STS/TIV	TITAN IV
STOWED LENGTH (M)	6.8	13.1	13.0	20.1
REACTOR DESIGN	7 ROD	7 ROD	1 ROD	1 ROD
CORE COOLABILITY	YES	YES	NO	NO
DOSE PLANE DEFINITION	10^{13} N/CM2 5×10^{5} RAD 4.5 M DIA	10^{13} N/CM2 5×10^{5} RAD 4.5 M DIA	10^{13} N/CM2 5×10^{5} RAD 4.5 M DIA	10^{13} N/CM2* 5×10^{5} RAD 2.0 M DIA
PUMP SELECTION	TEM	TEM	TEM	TEM
NUMBER OF LOOPS	12	12	12	4
POWER COND'G RESPONS'TY	TOTAL	TOTAL	BATT'S & CABLING	BATT'S & CABLING
SEPARATION DISTANCE (M)	22.5	22.5	22.5	42.1

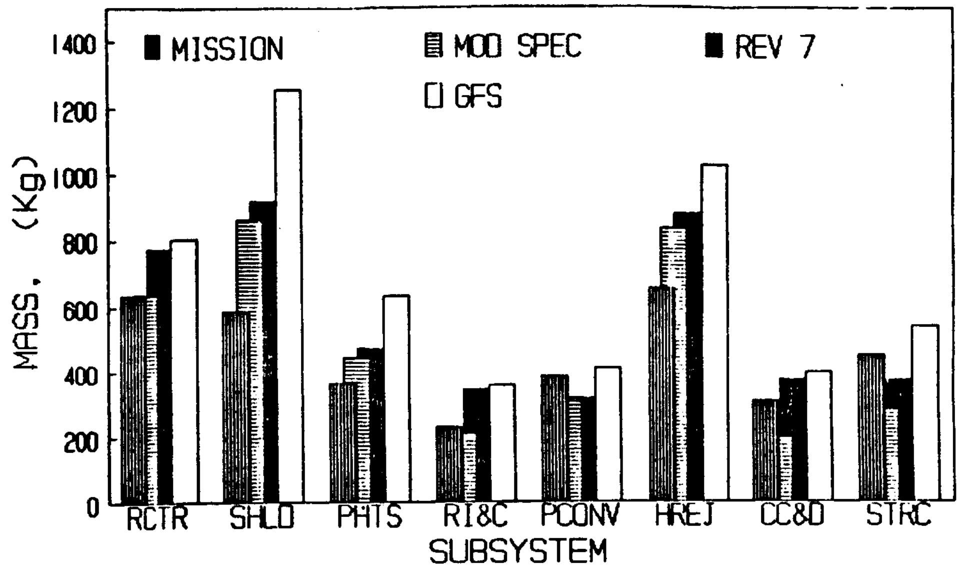
* - SPECIFIC MISSION DOSE PLANE REQUIREMENTS FOR MOST SENSITIVE COMPONENTS

SYSTEM PERFORMANCE PARAMETERS

	GFS AT SDR	GFS W/IN REV 7	GFS WITH SPEC MOD	SPECIFIC MISSION
REACTOR POWER (kWt)	2.4	2.3	2.3	2.2
PEAK REACT OUTLET TEMP (K)	1345/1375	1370/1400	1370/1400	1400
PRIMARY LOOP ΔT (K)	56	93	92	90
PRI. LOOP MASS FLOW (KG/S)	10.4	5.9	5.9	5.9
PEAK RAD INLET TEMP (K)	837	841	840	873
SECONDARY LOOP ΔT (K)	51	48	48	46
SEC. LOOP MASS FLOW (KG/S)	10.2	10.4	10.5	10.4
AVG. RAD SURF TEMP (K)	784	791	789	817
RAD BLACK BODY AREA (M^2)	104	94	96	81
RAD PHYSICAL AREA (M^2)	107	104	104	61
PC THERMOPILE AREA (M^2)	6.55	5.50	5.50	6.50
T/E LEG LENGTH (CM)	.68	.55	.55	.66
PC POWER GENERATED (kWe)	105.3	105.3	106.4	110.4

NOTE: PERFORMANCE PARAMETERS ARE EOM VALUES WITH ALL LOOPS OPERATING

SP-100 MASS MINIMIZATION RESULTS BY SUBSYSTEM



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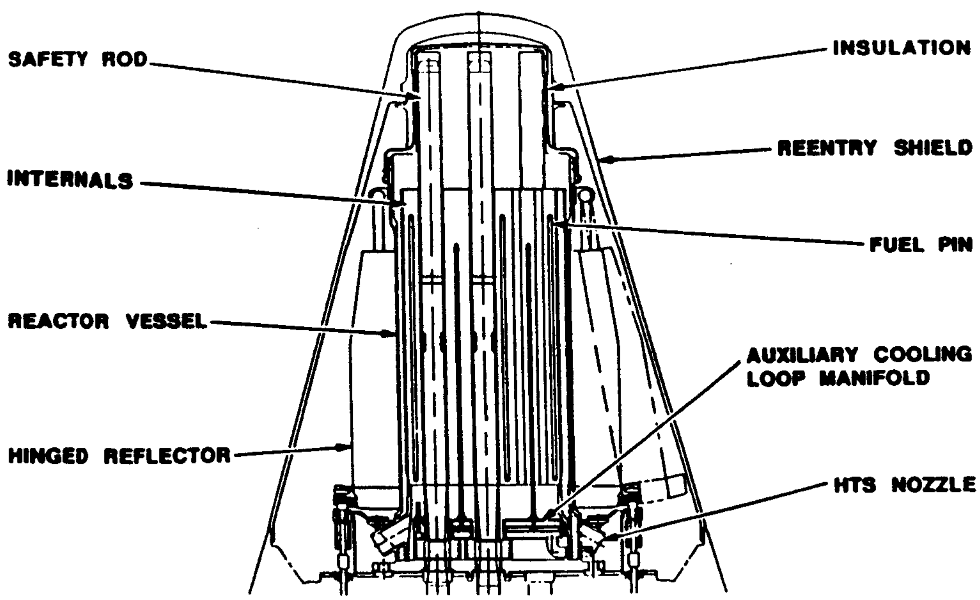
REACTOR SUBSYSTEM RSS COMPONENTS



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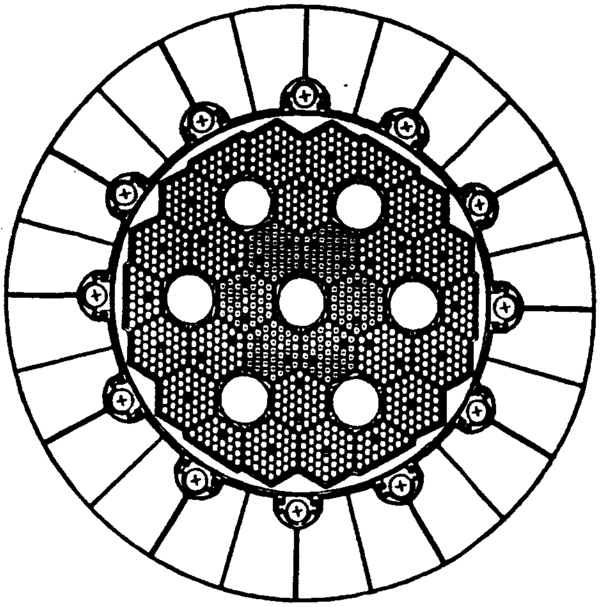
REACTOR CORE DESIGN



FUEL PIN	978
BAYONET TUBES	42
IN-CORE SAFETY RODS	7
RADIAL REFLECTORS	12
PIN DIAMETER (IN.)	.305
FUEL:	
ENRICHMENT (%)	97/89
PELLET DIA. (IN.)	.255
PELLET DEN. (% T.D.)	94.5
COLUMN HT. (IN.)	15.5

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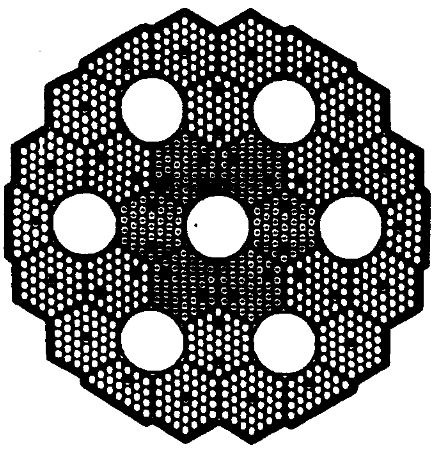
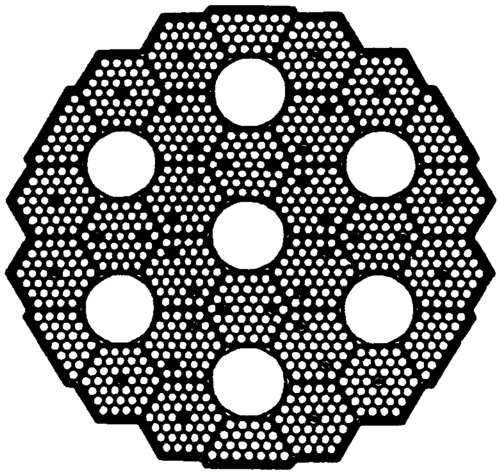
GFS WITHIN TECH SPEC REVISION 7
REACTOR SUBSYSTEM

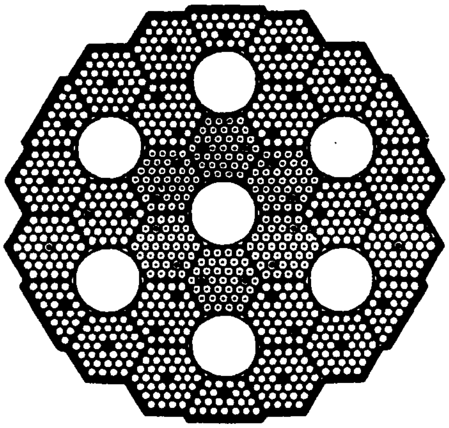


GFS AT SDR

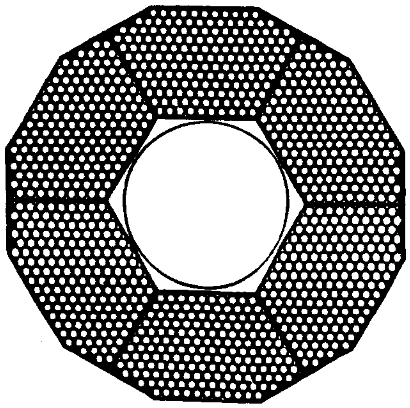


OPTIMIZED GFS
WITHIN REV. 7

GFS WITH TECH SPEC MODS
REACTOR SUBSYSTEM

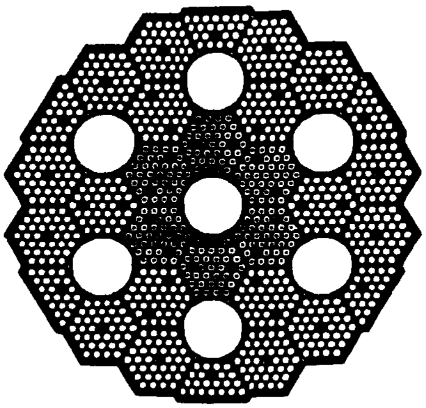


GFS AT SDR

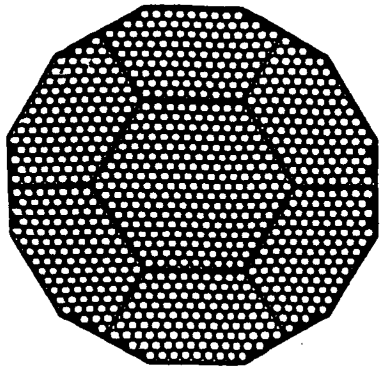


SINGLE SAFETY ROD, WITHOUT ACL

ADDITIONAL POTENTIAL
COMPACT REACTOR OPTION



GFS AT SDR



NO SAFETY RODS, WITHOUT ACL

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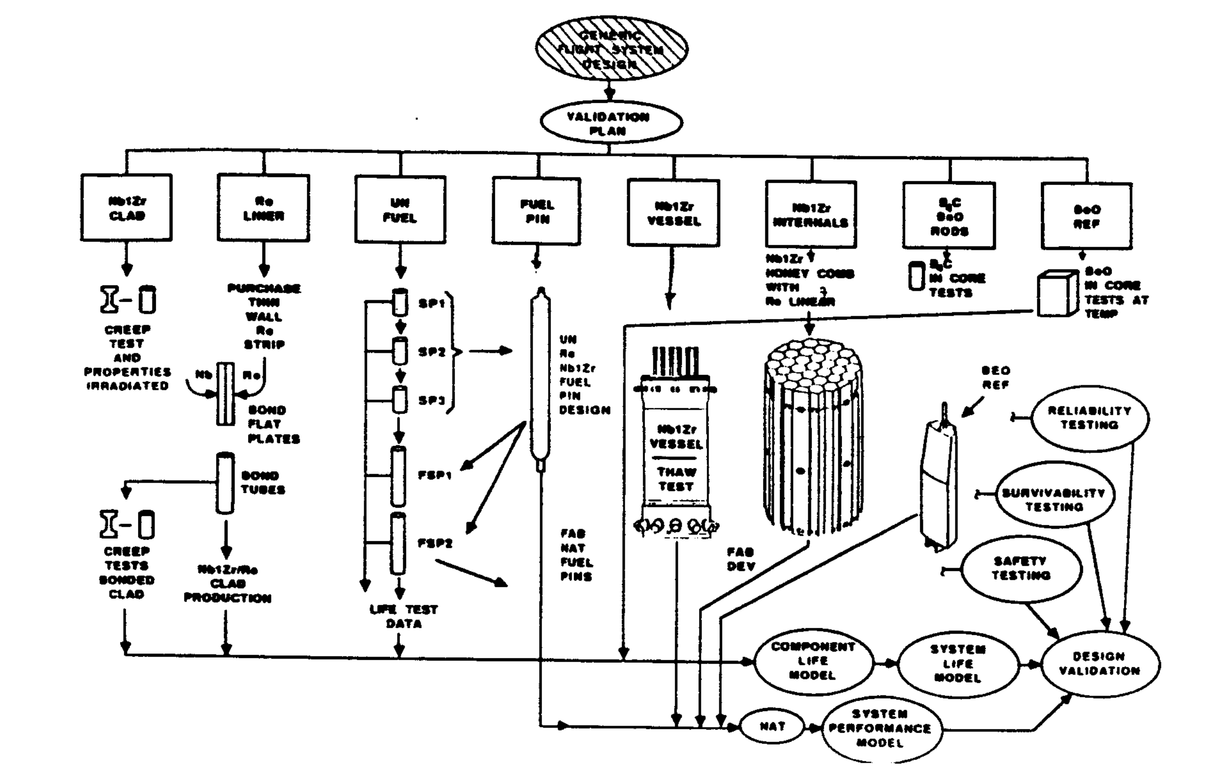
REACTOR SUBSYSTEM COMPONENT DEVELOPMENT BLOCK DIAGRAM



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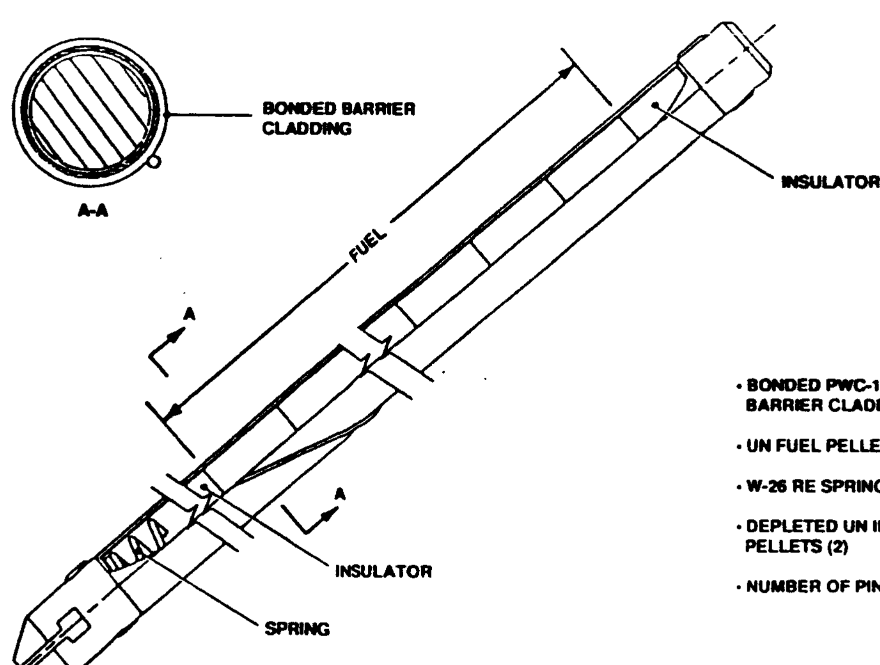
FUEL PIN DESCRIPTION



- BONDED PWC-11/RHENIUM BARRIER CLADDING
- UN FUEL PELLETS (59)
- W-26 RE SPRING
- DEPLETED UN INSULATOR PELLETS (2)
- NUMBER OF PINS – 978

JPL/LOS ALAMOS

NAT FUEL PRODUCTION RESULTS

Batch I.D.	Diameter Inch	Density % TD	Oxygen ppm	Carbon ppm	Iron ppm	X/U	Metal Phase Vol. %	Total µg/g Impurities
Specification	0.255 ± .001	94.5±1.5	<1000	<3000	<300	1.00-1.05	≤ 1	3000
Demonstration	0.2553	94.6	1020	1930	600	1.022	visible	<1250
Qualification	0.2551	94.3	600	2280	170	1.011	0.26	<1010
Insulators	0.2552	94.2	680	1430	40	1.007	0.22	< 520
First Production Lot	NA	93.5	1070	1230	NA	1.021	NA	NA
Second Production Lot	NA	95.4	520	940	NA	1.009	NA	NA

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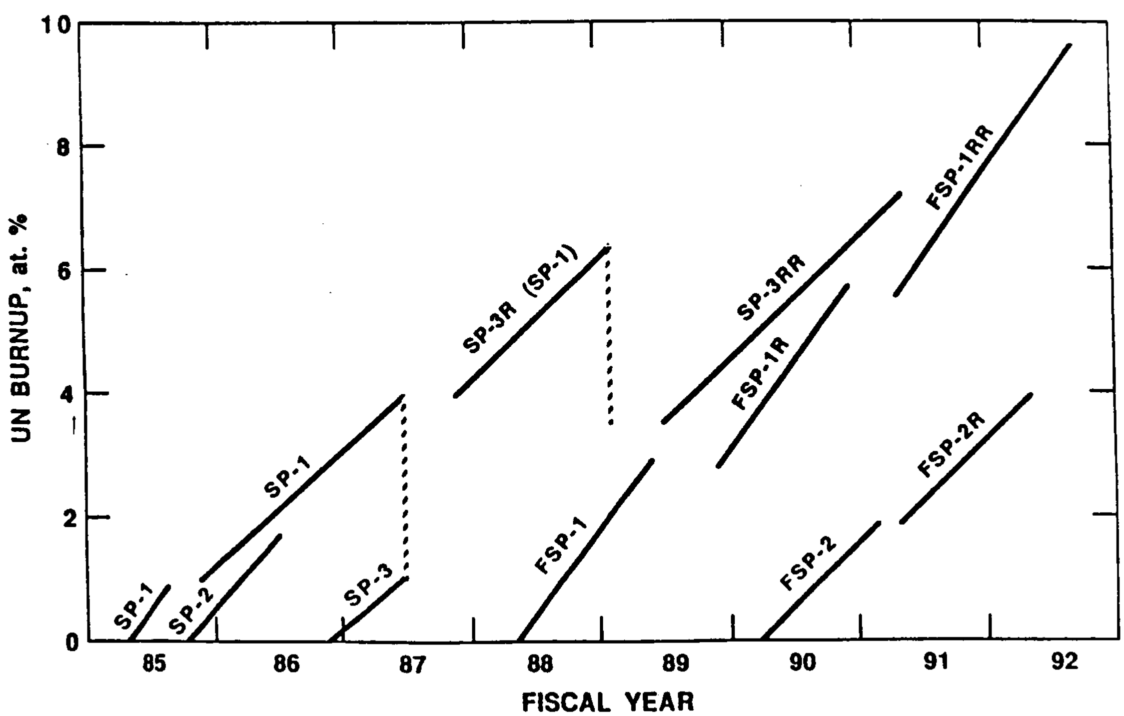
SP-100 FUEL PIN IRRADIATION SCHEDULE



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FUEL PIN SCREENING TEST: SP-3R

OBJECTIVE: PROVIDE LEAD DATA ON THE HIGH BURNUP PERFORMANCE OF UN FUEL AND Nb-1Zr CLADDING (THIRD IN A SERIES OF SCREENING TESTS)

STATUS: ACHIEVED 5.7% BURNUP (95% OF RFS PEAK) ON LEAD PIN, HIGH DENSITY FUEL HAS 2.7% BURNUP

TEST REMOVED JANUARY 1989. FUEL PINS WILL UNDERGO NONDESTRUCTIVE EXAMINATIONS

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PARAMETERS TESTED IN FSP-1

- CLADDING TEMPERATURE (1250, 1300, 1500 K)
- FUEL CENTERLINE TEMPERATURE (PIN DIAMETER) - (0.25, 0.30, 0.35)
- FUEL TEMPERATURE GRADIENT (FUEL POWER DENSITY) - (ENRICHMENT)
- FUEL DENSITY (85 TO 95% TD)
- FUEL STOICHIOMETRY (X/U = 1.00 TO 1.10)
- BURNUP (REPLICATE PINS FOR INTERIM EXAMINATION)
- FUEL-CLADDING GAP
- ANNULAR PELLETS (CENTER HOLE)
- LINER MATERIAL (Re VS W)
- LINER DESIGN (SEALED, FREE STANDING, SHORT)

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FUEL PIN IRRADIATION TESTING: FSP-1

OBJECTIVE: ENGINEERING SCALE PARAMETRIC TEST TO PROVIDE DATA TO OPTIMIZE FUEL FABRICATION, VERIFY LINER SELECTION, AND VALIDATE RFS

DESCRIPTION: 38 ONE-FOOT LONG FUEL PINS IRRADIATED IN LITHIUM-FILLED CAPSULES. WITH PLANNED RECONSTITUTIONS, A TOTAL OF 72 FUEL PINS COVERING A BURNUP RANGE OF 2.5% TO 8.5%

STATUS: TWO ATOM % BURNUP, CONTINUING IRRADIATION IN FFTF

REMOVED IN JANUARY 1989 FOR FIRST INTERIM EXAMINATION AND RECONSTITUTION

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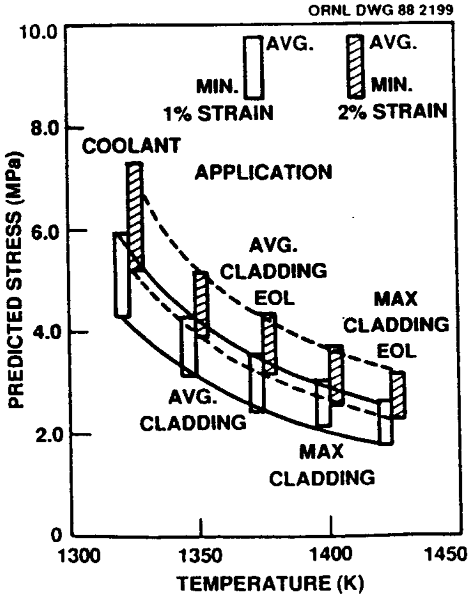
MECHANICAL PROPERTIES TESTING

THE CREEP DATA AVAILABLE ON Nb-1Zr HAVE BEEN ANALYZED TO PREDICT STRESSES THAT WILL PRODUCE 1 AND 2% CREEP STRAIN IN SEVEN YEARS



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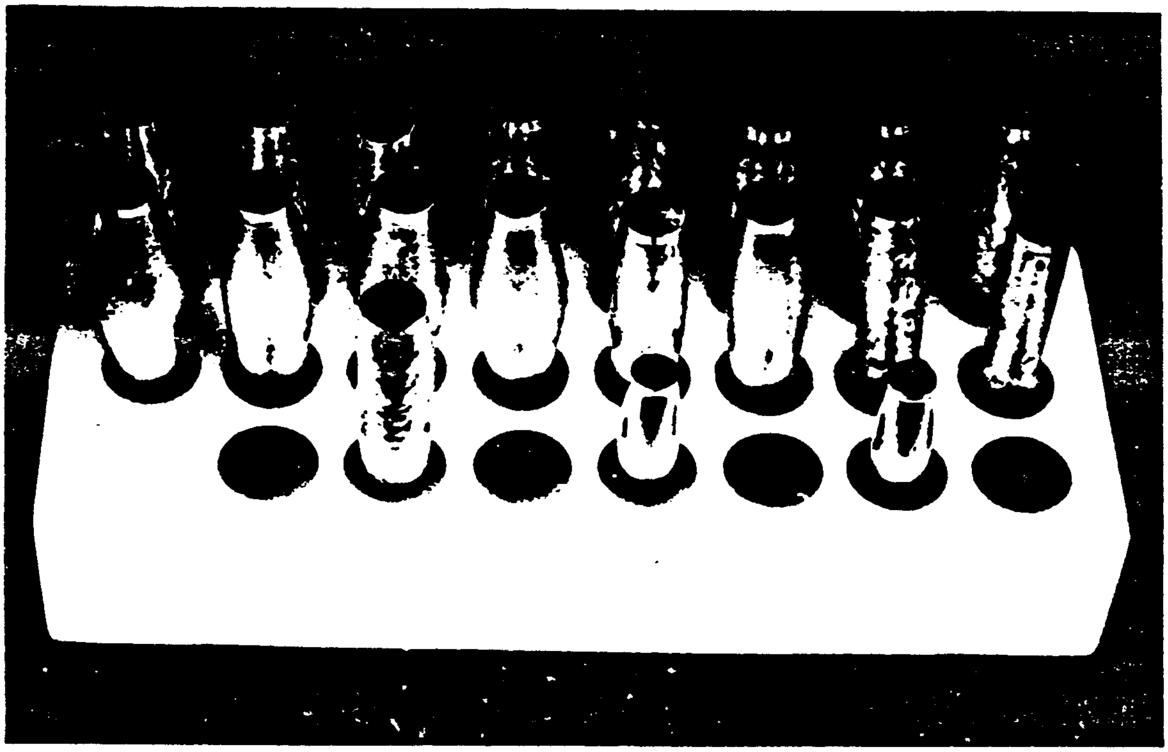
LOCA PRESSURIZED Nb-1Zr TUBES



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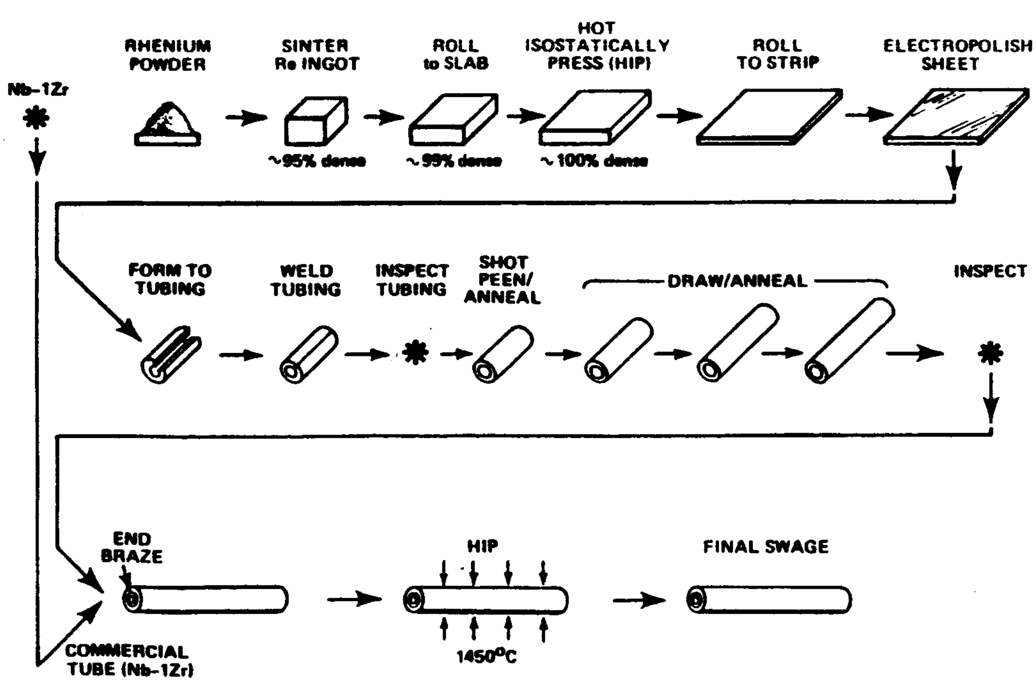
FABRICATION OF Nb-1Zr/Re BONDED TUBING



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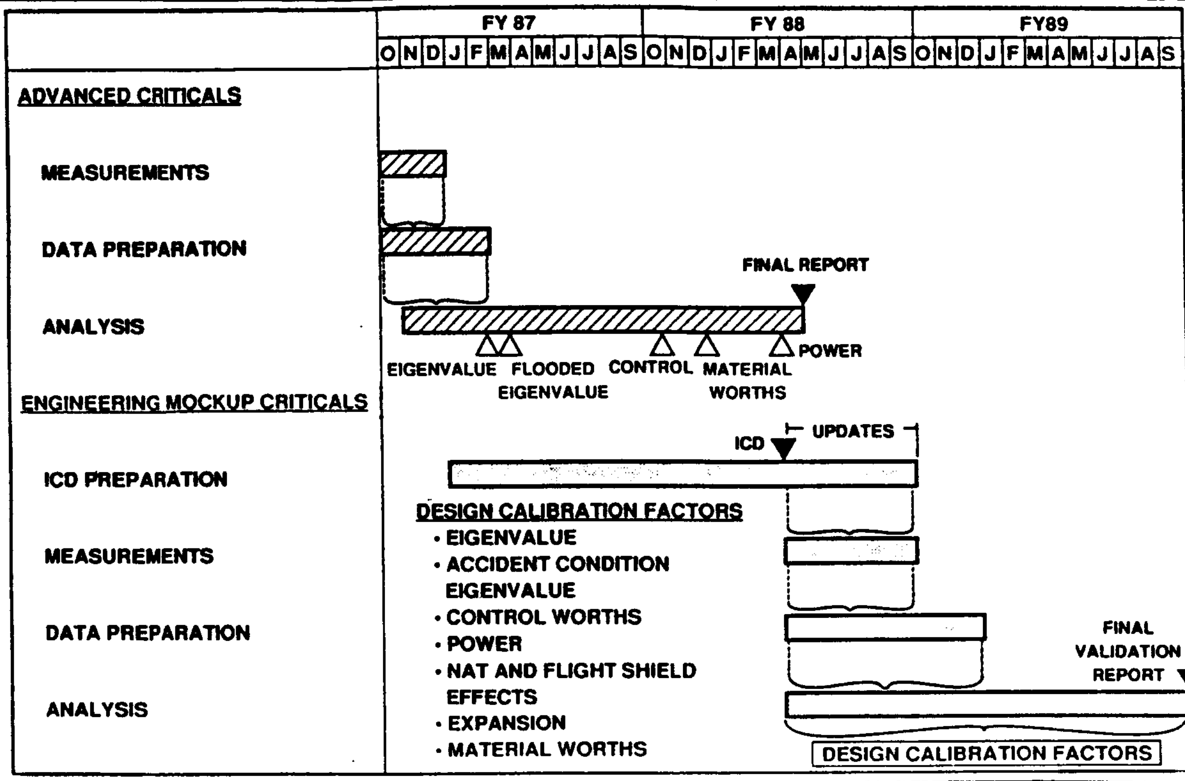
REACTOR CRITICAL EXPERIMENT SCHEDULE



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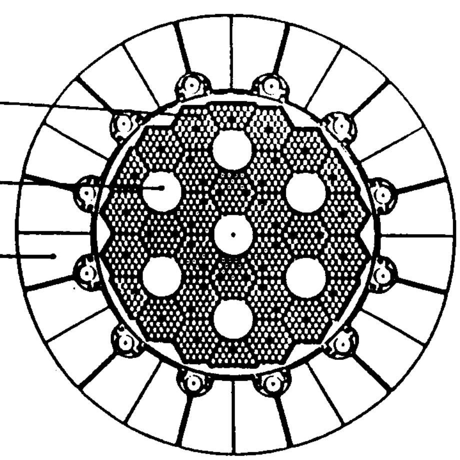
SP-100 DESIGN ANALYSIS VALIDATED BY EMC

- FUEL ENRICHMENT SPECIFICATION
- SAFETY ROD DESIGN
- REFLECTOR DESIGN
- POWER DISTRIBUTION PREDICTIONS
- REACTIVITY FEEDBACK PREDICTIONS
- COMPARISON ON NAT AND GFS CORE PERFORMANCE
- FLOODING AND EARTH BURIAL ACCIDENT CONDITION ANALYSIS



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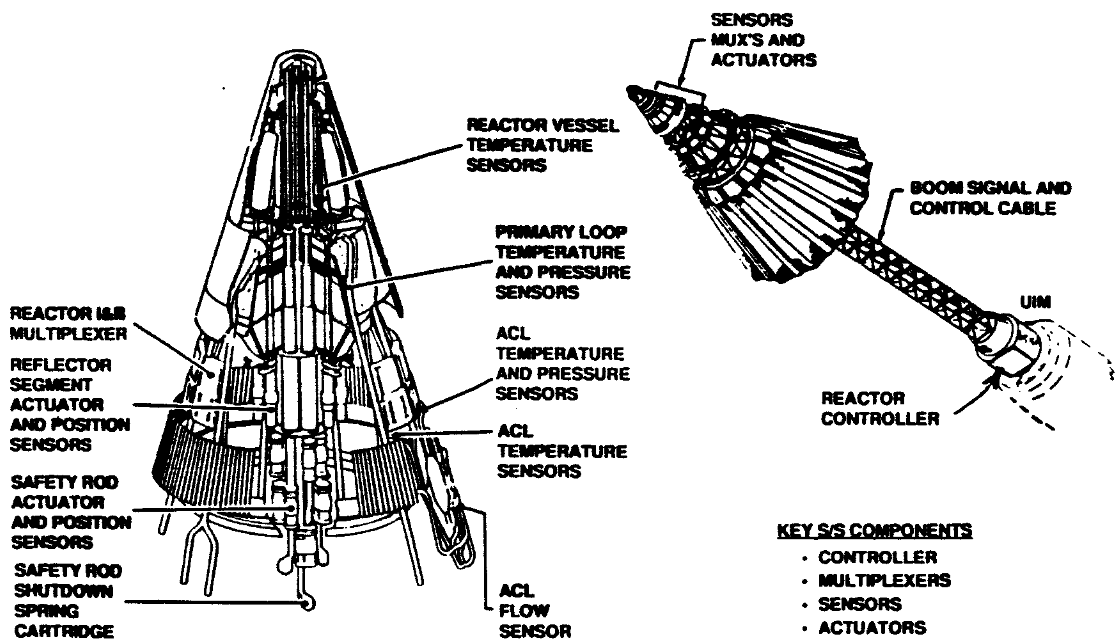
REACTOR INSTRUMENTATION AND CONTROL SUBSYSTEM RI&CSS COMPONENTS



KEY S/S COMPONENTS

- CONTROLLER
- MULTIPLEXERS
- SENSORS
- ACTUATORS

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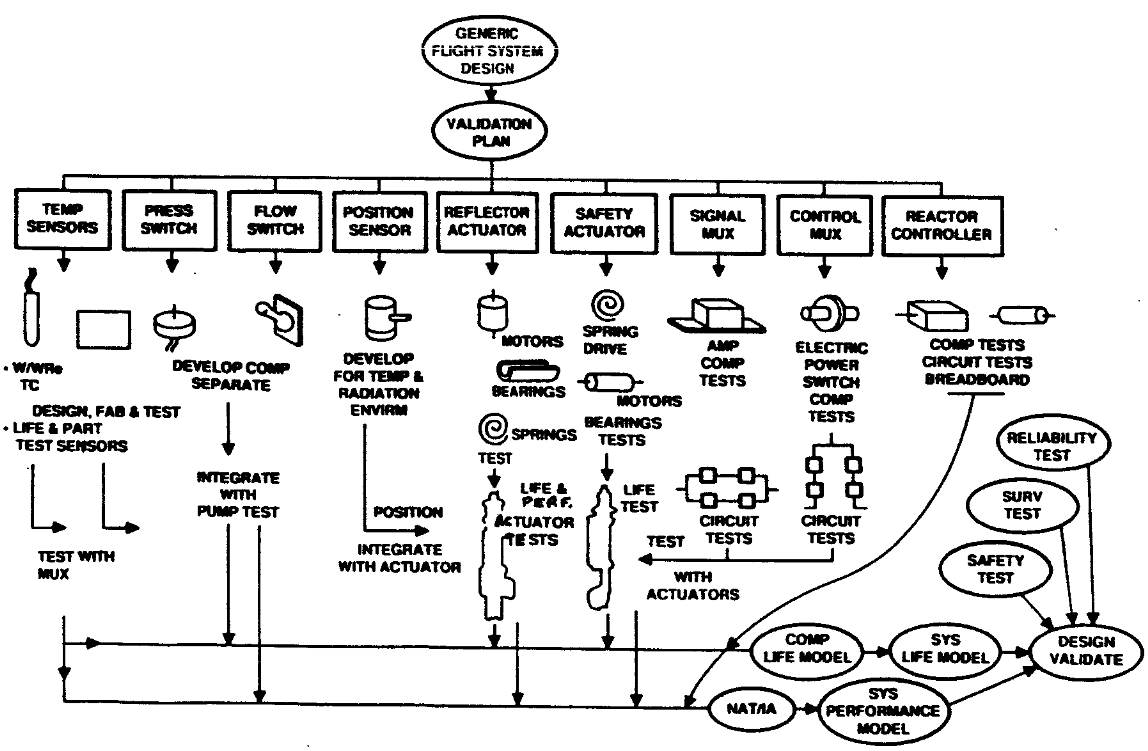
REACTOR I&C SUBSYSTEM COMPONENT DEVELOPMENT BLOCK DIAGRAM



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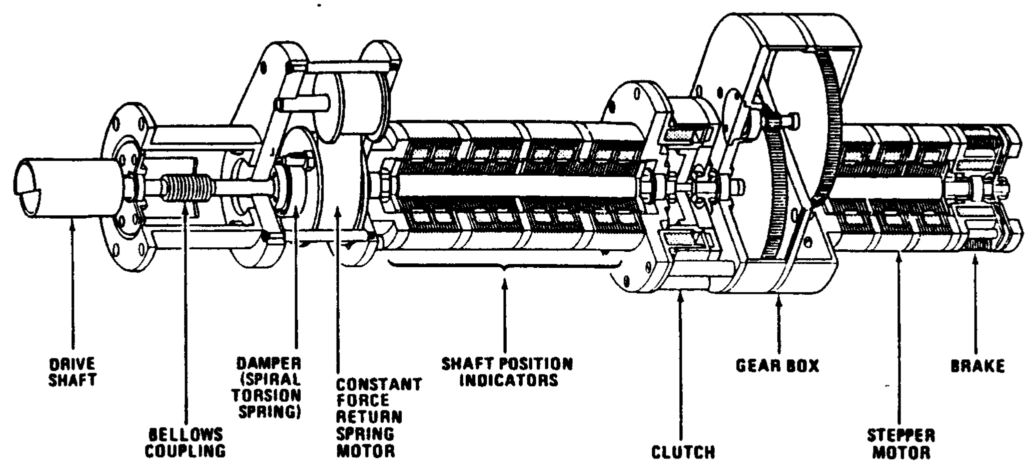
REACTOR INSTRUMENTATION AND CONTROL SUBSYSTEM SAFETY ROD DRIVE ACTUATOR



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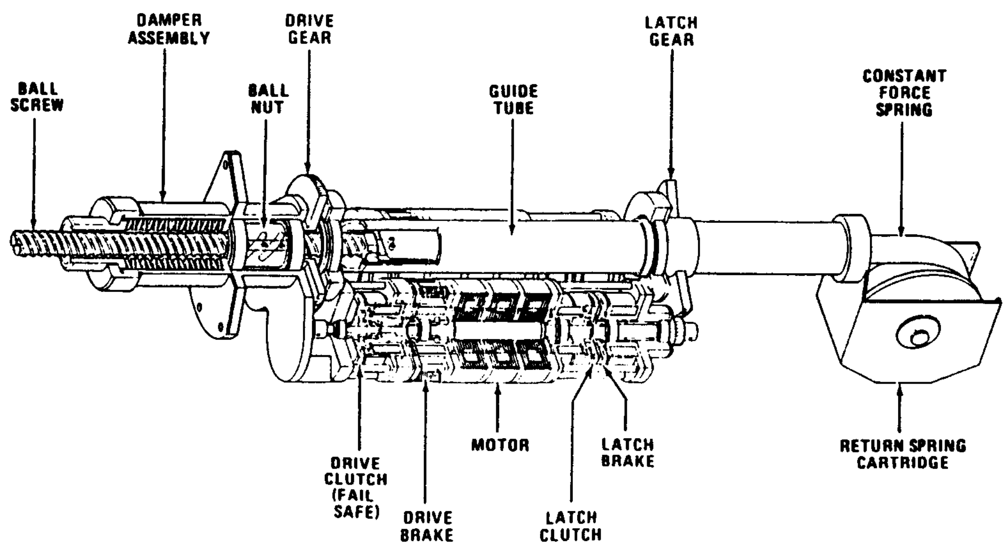
REACTOR INSTRUMENTATION AND CONTROL SUBSYSTEM REFLECTOR DRIVE ACTUATOR



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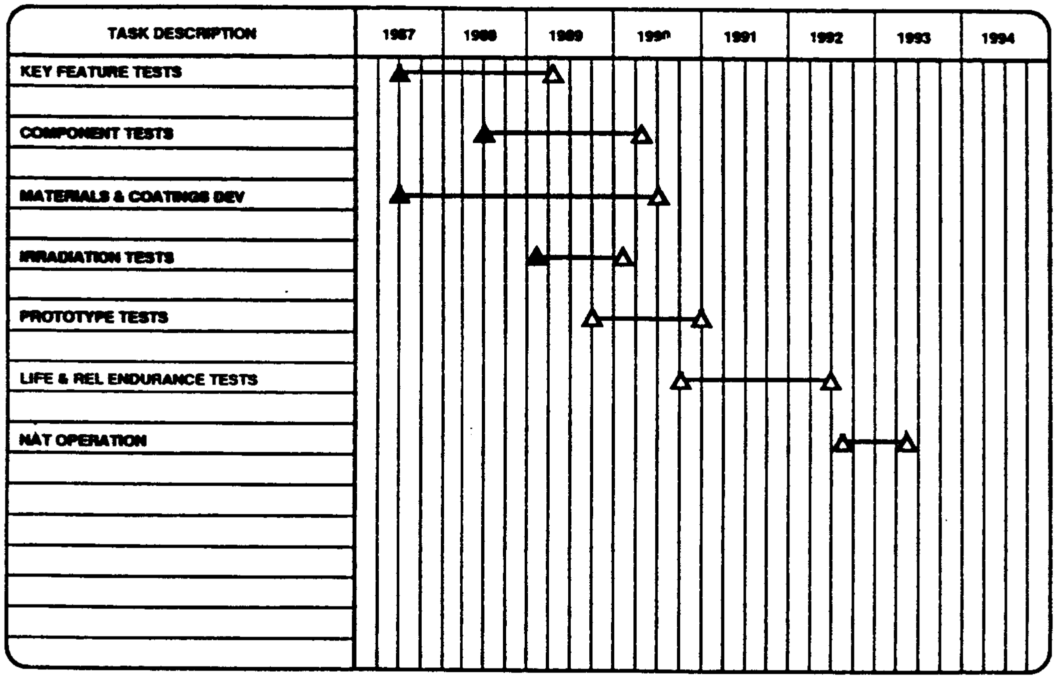
JPL/LOS ALAMOS

REACTOR INTRUMENTATION AND CONTROL SUBSYSTEM DEVELOPMENT SCHEDULE



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JFM ??

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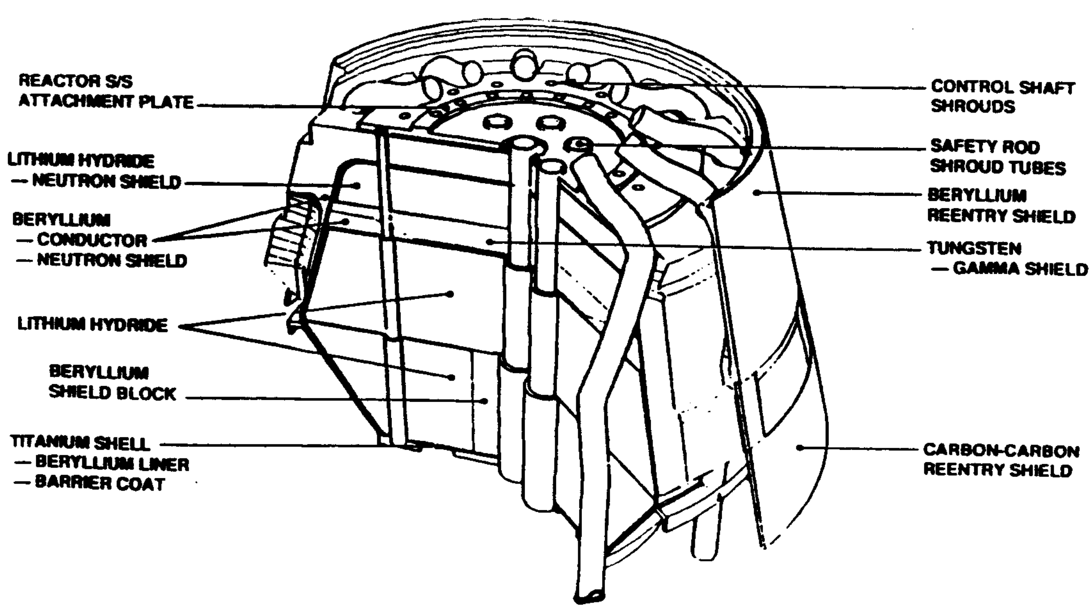
SHIELD SUBSYSTEM SSS COMPONENTS



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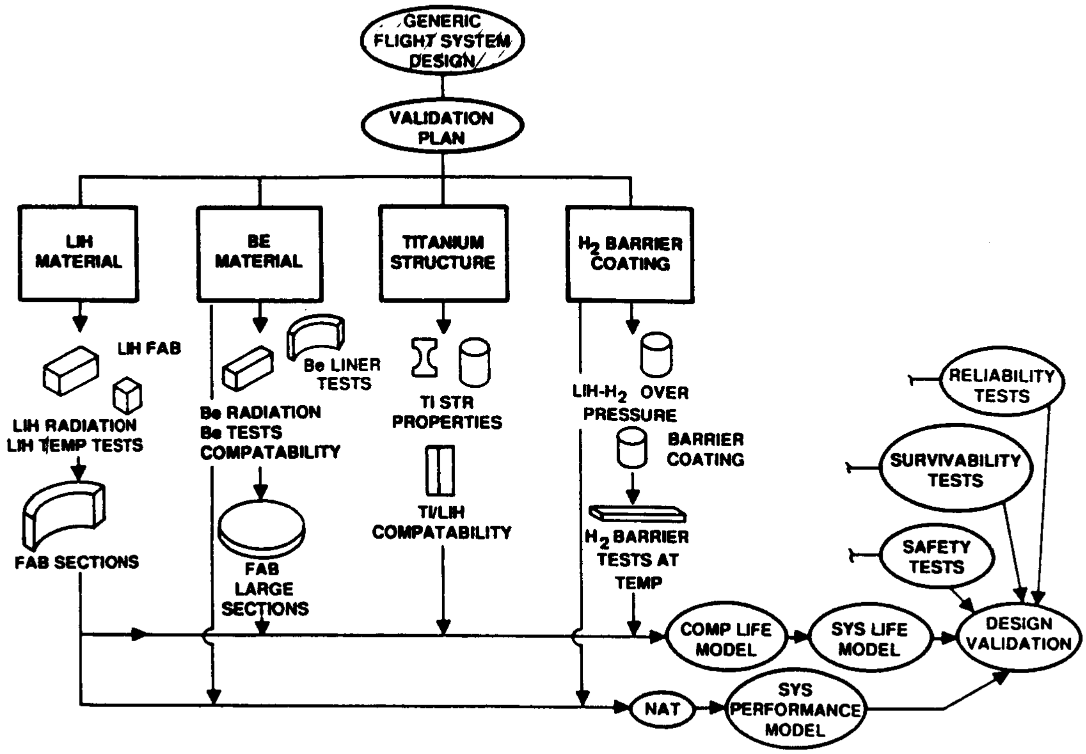
JFM 33

JPL/LOS ALAMOS

SHIELD SUBSYSTEM COMPONENT DEVELOPMENT BLOCK DIAGRAM



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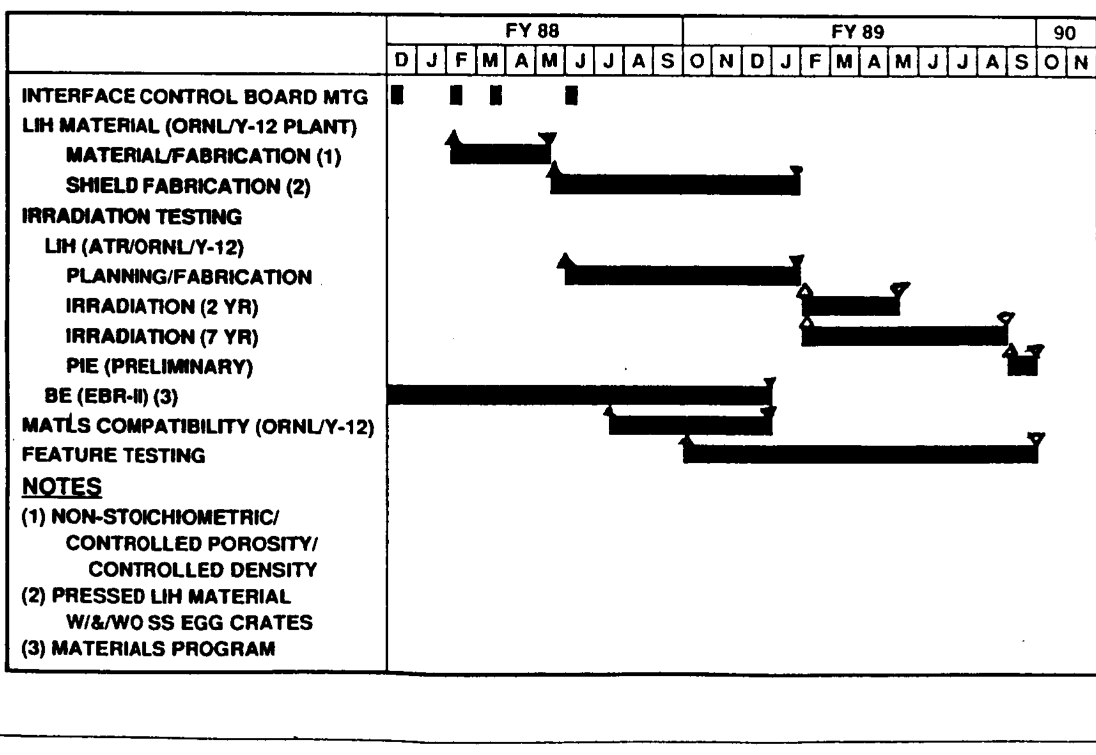
JPL/LOS ALAMOS

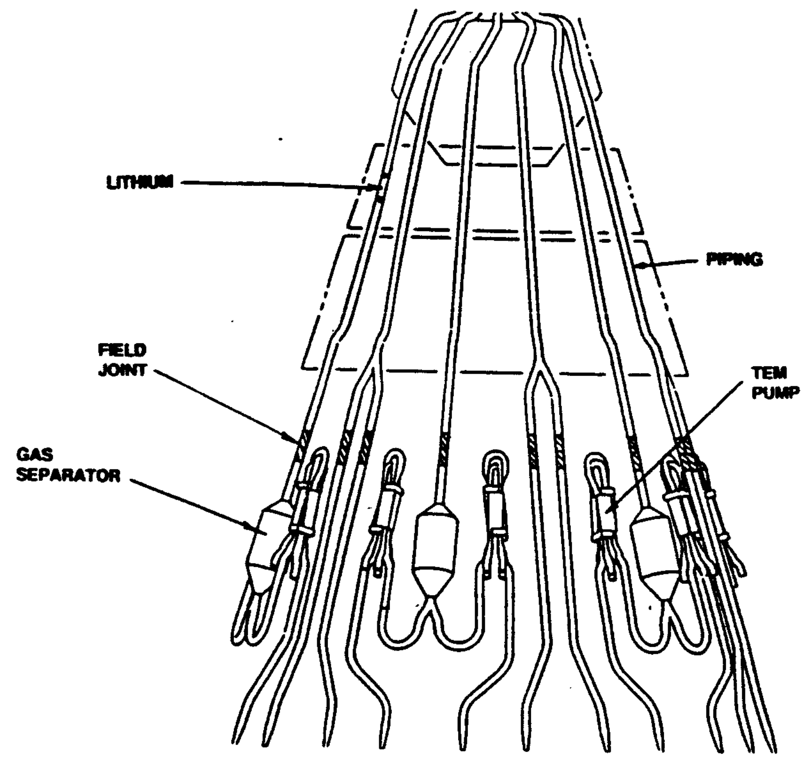
SHIELD SUBSYSTEM SCHEDULE - SHIELD MATERIALS DEVELOPMENT



2-8-89

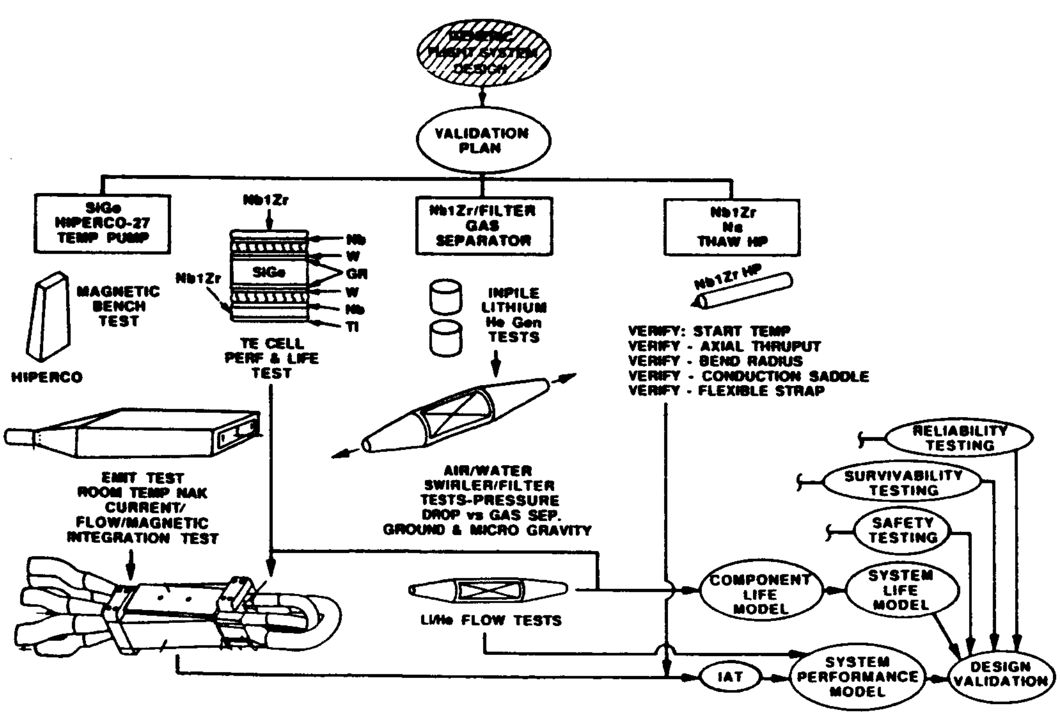
JFM 37

JPL/LOS ALAMOS	HEAT TRANSPORT SUBSYSTEM HTSS COMPONENTS	



2-8-89 JFM 38

JPL/LOS ALAMOS	HEAT TRANSPORT SUBSYSTEM COMPONENT DEVELOPMENT	



2-8-89 JFM 39

JPL/LOS ALAMOS

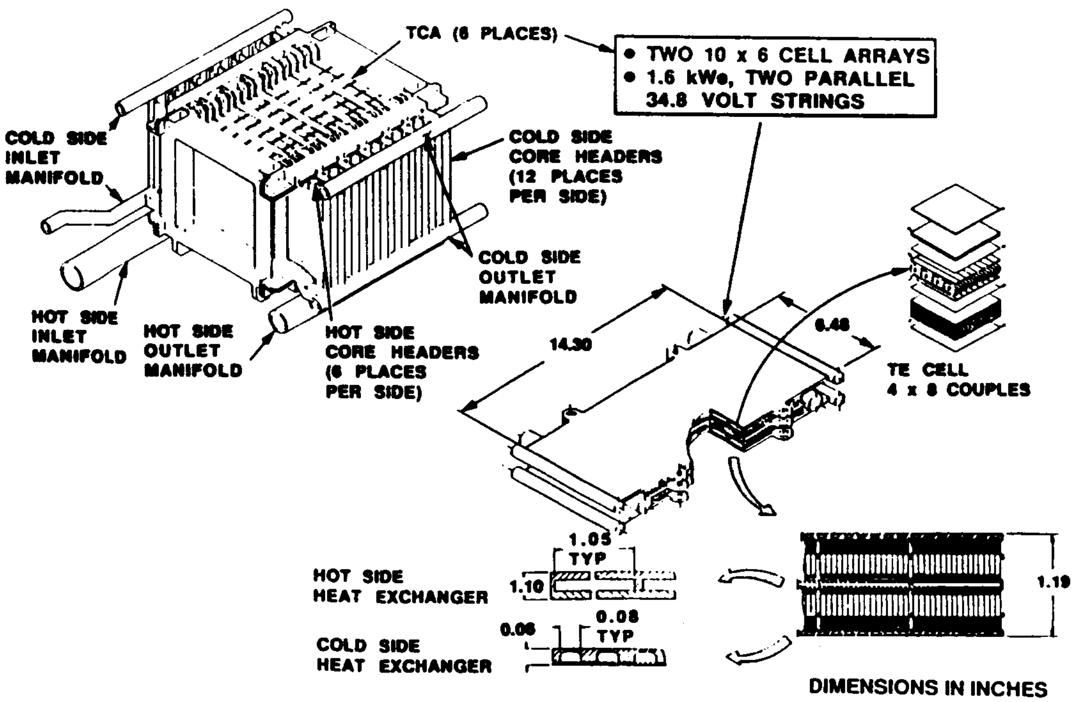
HEAT TRANSPORT SUBSYSTEM SUMMARY OF ACCOMPLISHMENTS

- COMPLETED MAGNETIC BENCH TEST
  - PREDICTED MAGNETIC PERFORMANCE
  - COMPLETED TESTING OF SOLID AND SLOTTED CONNECTING BUS WITH MAGNETIC STRUCTURE
  - VERIFIED PREDICTION ANALYSIS
- COMPLETED EMIT PRELIMINARY DESIGN
- GAS SEPARATOR CONCEPT DEVELOPED
- COMPLETED SEPARATOR AIR/WATER TEST
  - PREDICTED PERFORMANCE
  - VERIFIED PERFORMANCE

2-8-89

JPL/LOS ALAMOS

POWER CONVERTER SUBSYSTEM PCSS COMPONENTS



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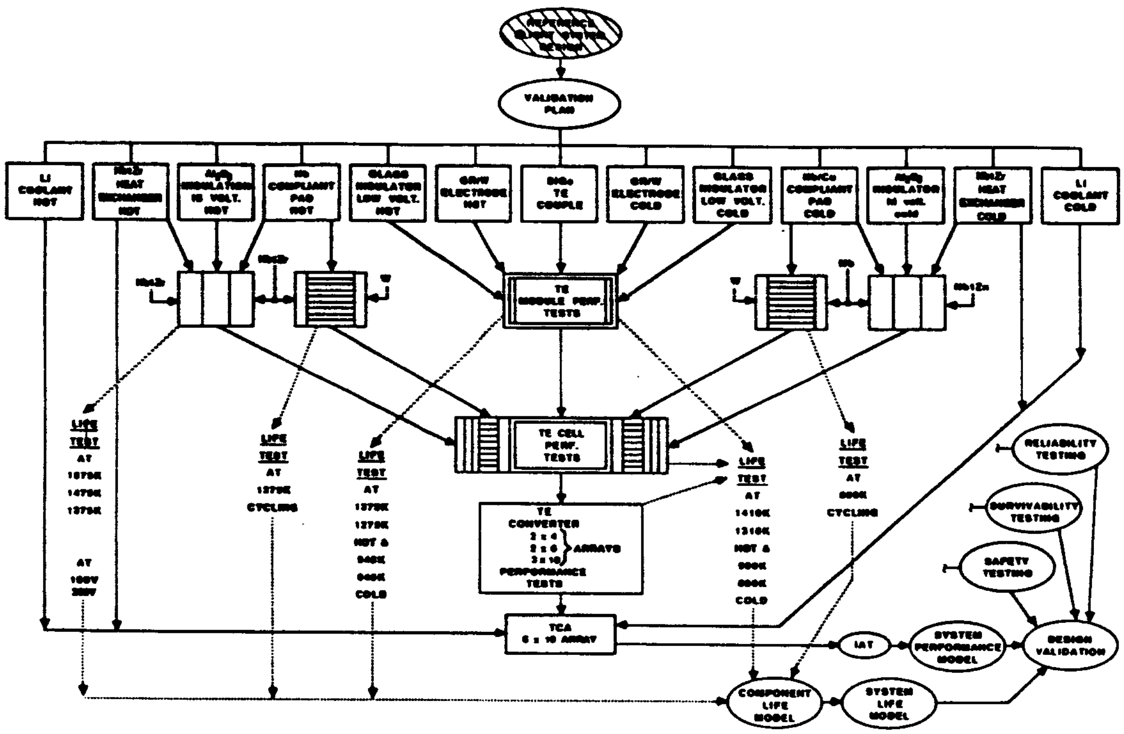
POWER CONVERSION SUBSYSTEM COMPONENT DEVELOPEMENT BLOCK DIAGRAM



2-8-89 JFM 46

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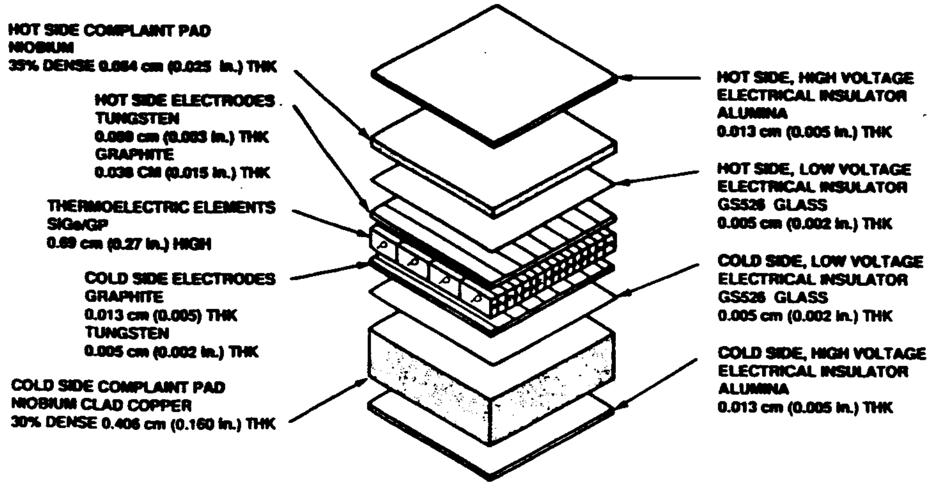
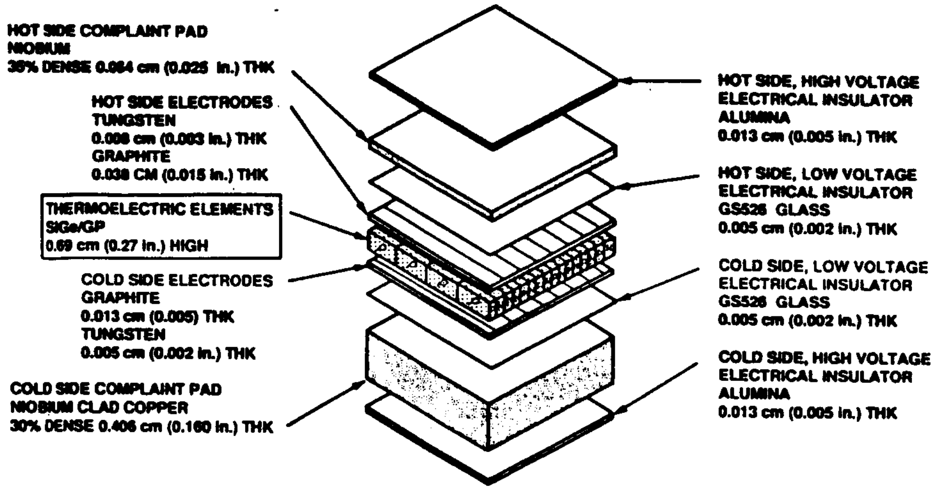
TE CELL CONFIGURATION



2-8-89 JFM 47

JPL/LOS ALAMOS

THERMOELECTRIC ELEMENTS



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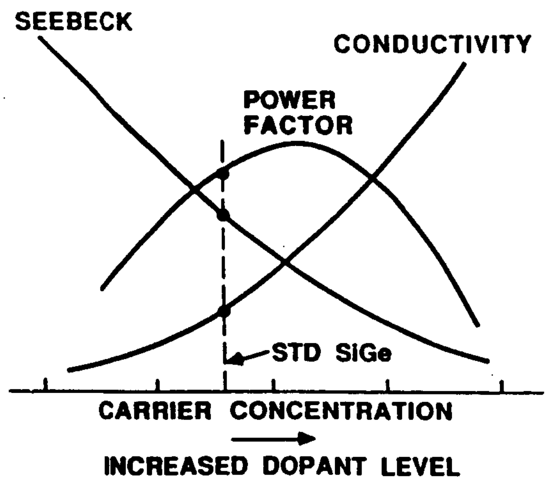
JFM 48

JPL/LOS ALAMOS

IMPROVED T/E MATERIAL



- OPTIMUM POWER FACTOR OCCURS AT SEEBECK COEFFICIENT OF 172 μV/K
- STANDARD SiGe IS UNDERDOPED BECAUSE OF SOLUBILITY LIMIT OF PHOSPHORUS
- IMPROVEMENTS ARE AIMED TO:
  - INCREASE DOPANT LEVEL
  - DECREASE THERMAL CONDUCTIVITY

$$\text{FIGURE OF MERIT} = \frac{\text{POWER FACTOR}}{\text{THERMAL CONDUCTIVITY}}$$

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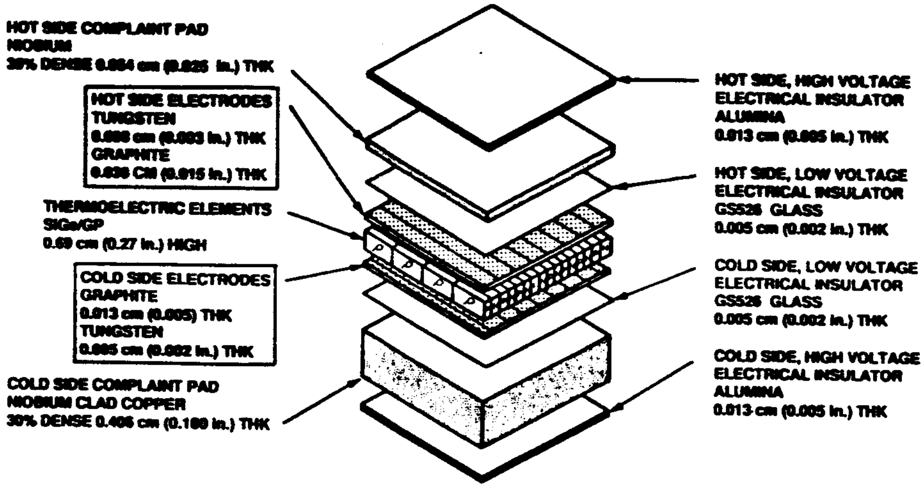
JFM-49

JPL/LOS ALAMOS

ELECTRODES



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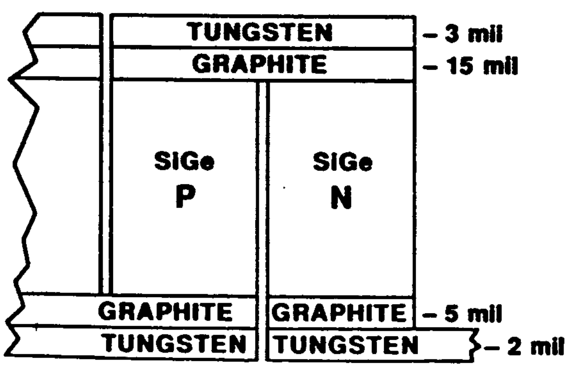
JPL/LOS ALAMOS

ELECTRODE/CONTACT



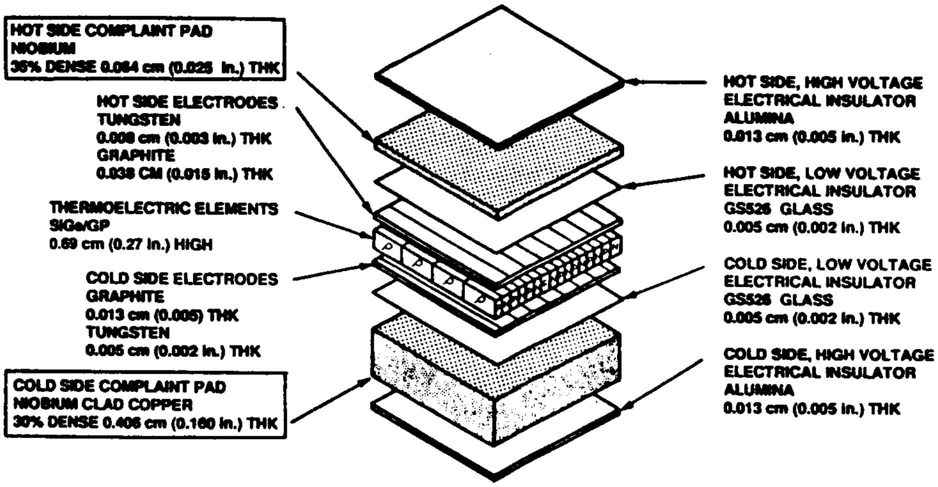
- TUNGSTEN/SILICON FORM WSi_2 WHICH LEADS TO FAILURE
- GRAPHITE IS REQUIRED AS DIFFUSION BARRIER
- TUNGSTEN IS DESIRED FOR:
  - LOW RESISTIVITY
  - COLD END STRAP
- CURRENT TECHNOLOGY (RTG) IS SiMo ELECTRODE ON HOT SIDE – ALL TUNGSTEN ON COLD SIDE (LOWER TEMPERATURE)

2-8-89

JEM 51

JPL/LOS ALAMOS

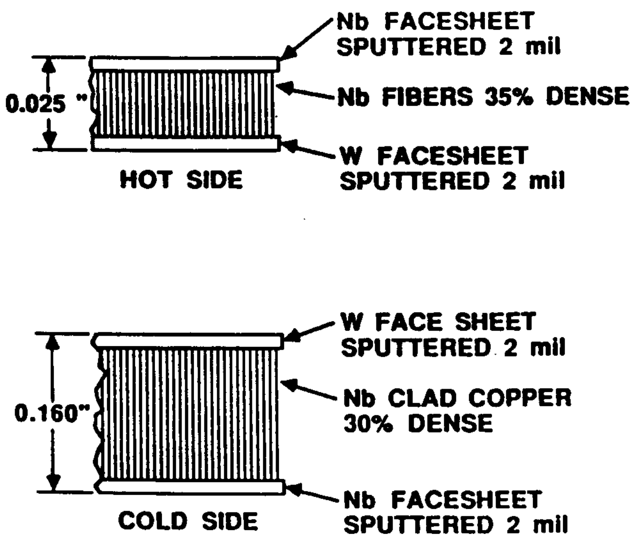
COMPLAINT PAD



2-8-89 JFM 53

JPL/LOS ALAMOS

COMPLAINT PAD

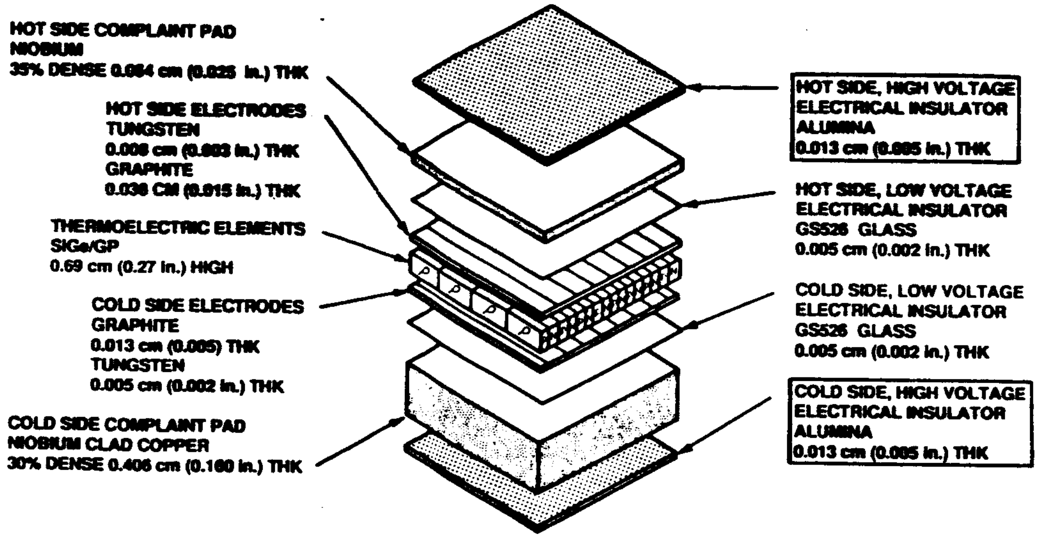


- SPUTTERING OF Nb/Nb FACESHEET HAS BEEN SUCCESSFUL – TENSILE TESTS ARE UNDERWAY
- SPUTTERING OF Nb/W AND W/W ARE SCHEDULED
- SUCCESSFULLY DRAWN WIRES FOR COLD SIDE Nb CLAD COPPER TO 0.005 In. DIA USING 583 FILAMENTS AT 0.14 mil
- ANALYZED DATA FROM DEFLECTION TESTS (W PADS) AND CORRELATED WITH THEORETICAL PREDICTIONS

2/8/89 JFM-54

JPL/LOS ALAMOS

HIGH VOLTAGE ELECTRICAL INSULATOR

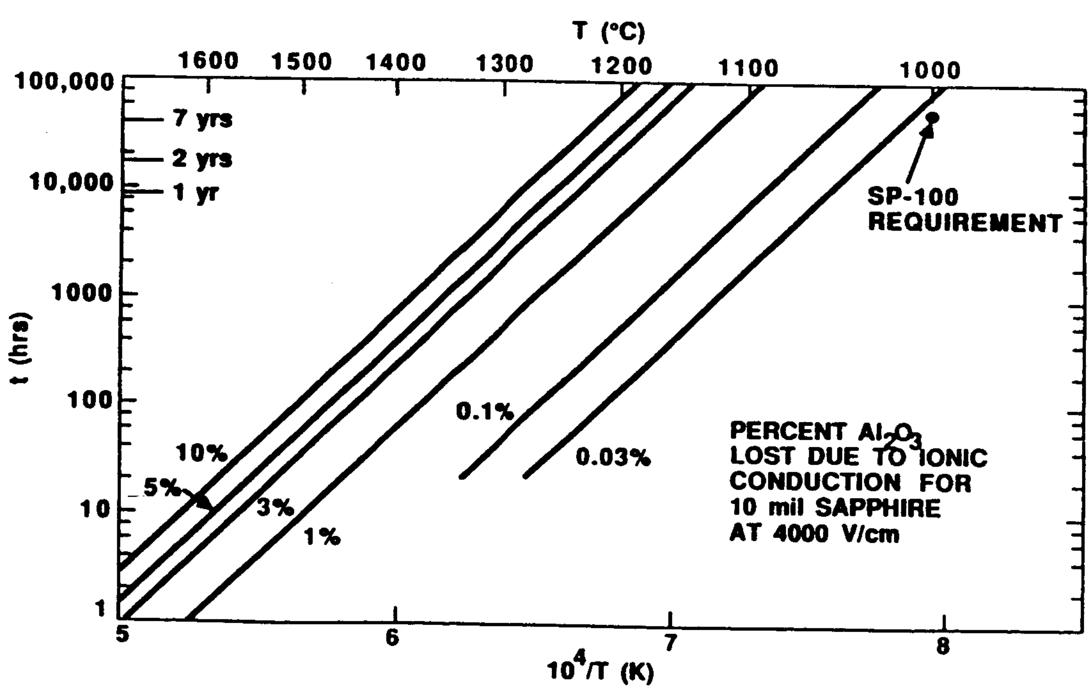


2/8/89

JFM 56

JPL/LOS ALAMOS

PREDICTED SAPPHIRE BEHAVIOR



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JFM 58

JPL/LOS ALAMOS

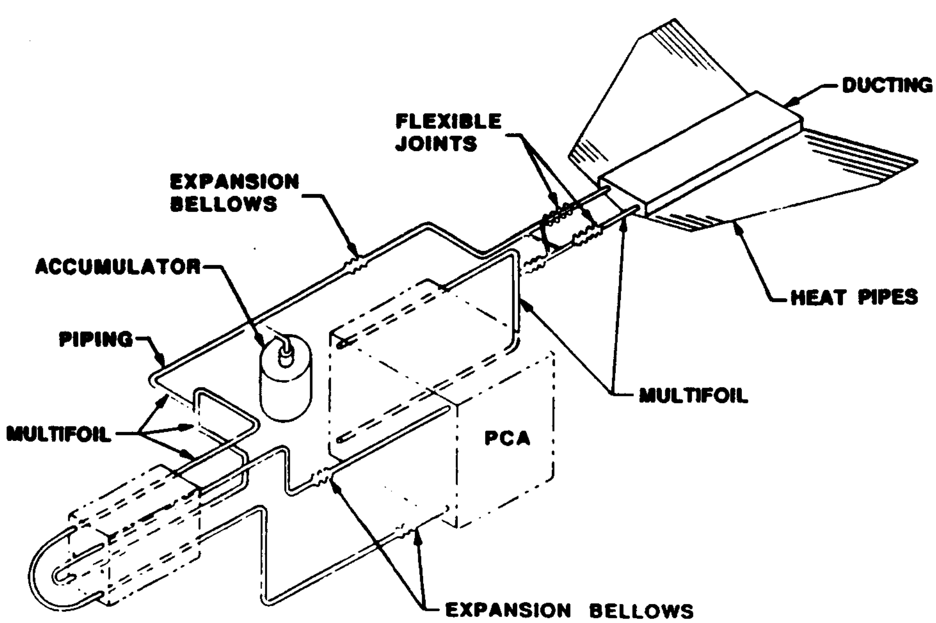
T/E CELL ASSEMBLY

- FIRST TYPE OF CELLS TO BE ASSEMBLED IS DESIGNATED PD-1 CELL
- OPERATING CONDITIONS OF PD-1 CELL HAVE BEEN SELECTED
- STRESS ANALYSIS FOR PD-1 CELL SHOWS POSITIVE MARGINS FOR ALL COMPONENTS

2-8-89

JPL/LOS ALAMOS

HEAT REJECTION SUBSYSTEM HRSS COMPONENTS



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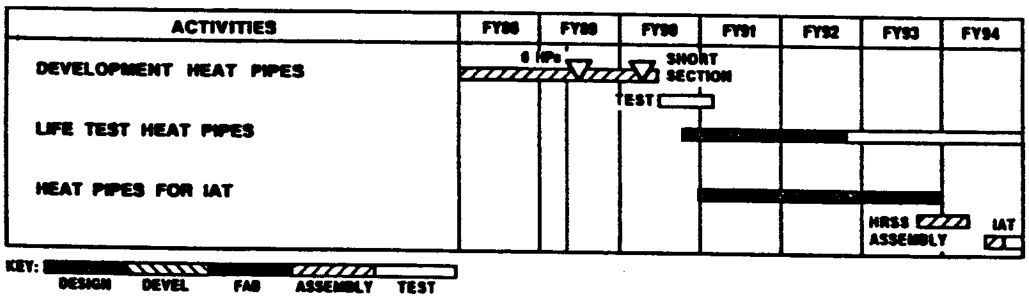
JFM 6

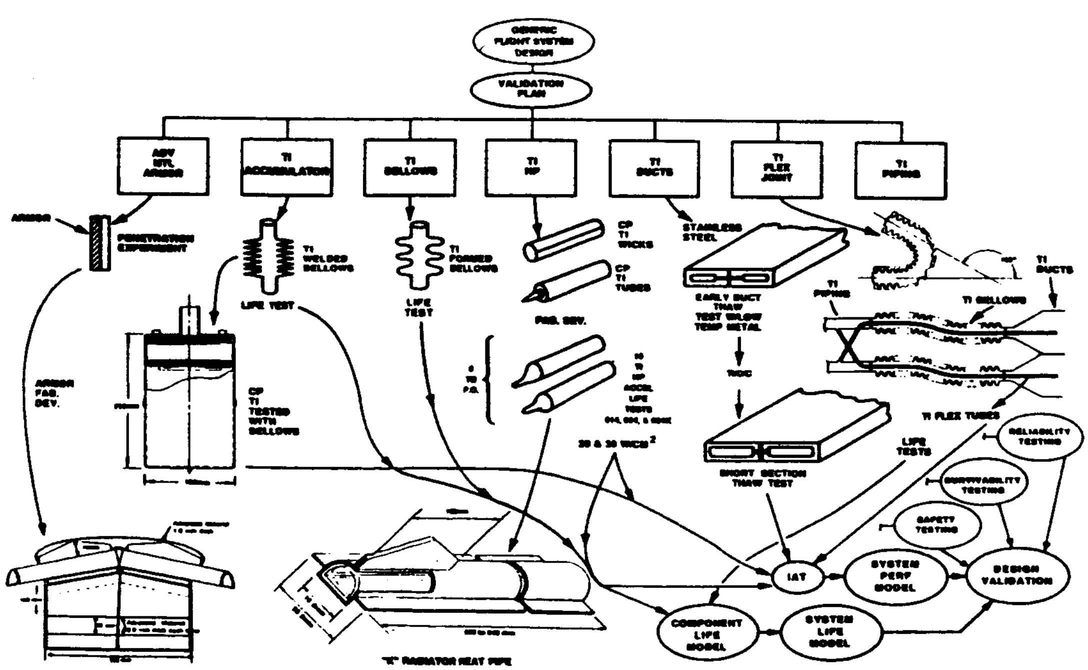
JPL/LOS ALAMOS	HEAT PIPES

- FY88 ACCOMPLISHMENTS
  - BUILT 8 HEAT PIPES (4 Nb AND 4 Ti)
  - BUILT 4 WICK DESIGNS (2 FOIL AND 2 HYBRID FOIL/SINTERED)
  - DEMONSTRATED FOIL WICK FABRICATION PROCESS FOR Ti AND Nb (BACKUP HARDENED DESIGN)
  - DEMONSTRATED DESIGN GOAL OF 30 W/cm² RADIAL FLUX (SINGLE FOIL IN Nb PIPE)
- HP CHARACTERISTICS
  - ≈ 5/8 in. DIA BY 0.6 m TO 1.2 m LONG
  - POTASSIUM WORKING FLUID
  - Ti FOIL WICK (SINGLE OR DOUBLE)
  - Ti TUBE
  - ARMOR IS C/C
  - 50 HEAT PIPES IN IAT (NO ARMOR)



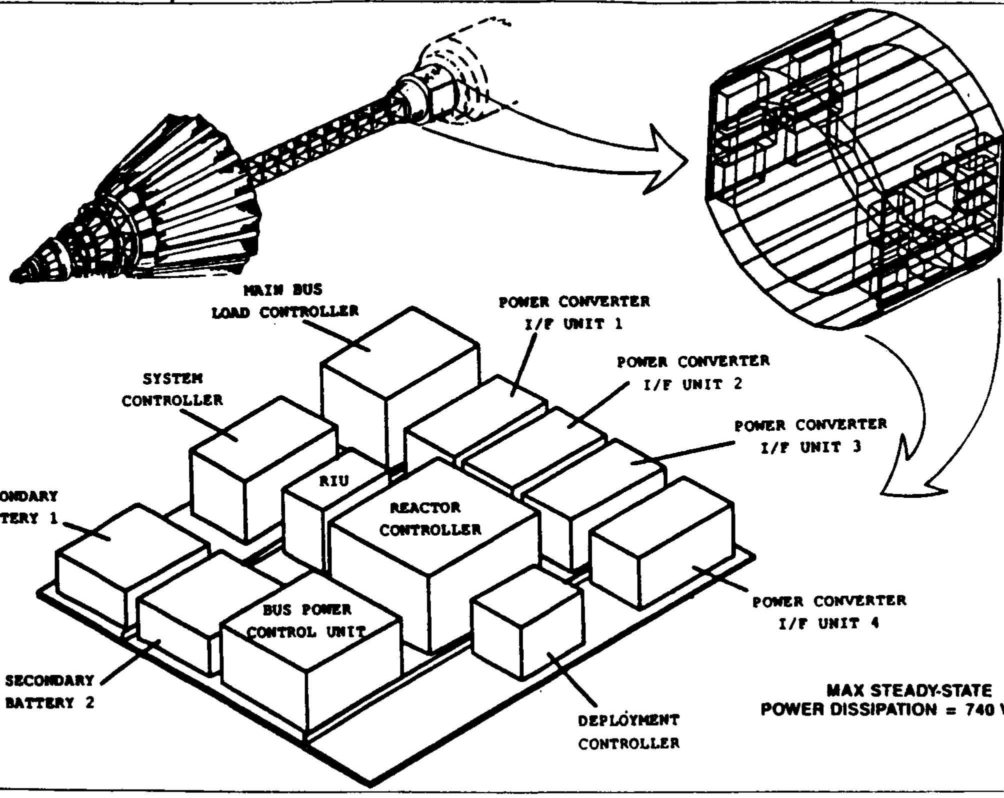
2/8/89 JFM

JPL/LOS ALAMOS	HEAT REJECTION SUBSYSTEM BLOCK COMPONENT DEVELOPMENT DIAGRAM



2-8-89 JFM 62

JPL/LOS ALAMOS	POWER CONDITIONING, CONTROL AND DISTRIBUTION SUBSYSTEM PCC&D SS COMPONENTS	

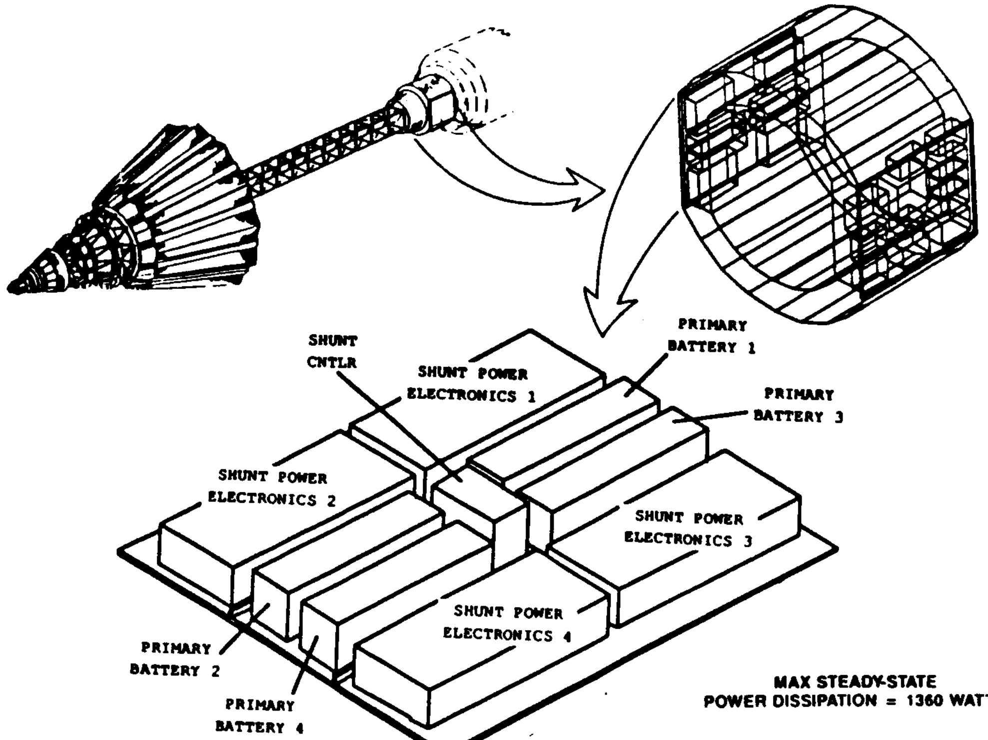


MAX STEADY-STATE POWER DISSIPATION = 740 WATTS

2-8-89

JFM 66

JPL/LOS ALAMOS	POWER CONDITIONING, CONTROL AND DISTRIBUTION SUBSYSTEM PCC&D SS COMPONENTS	

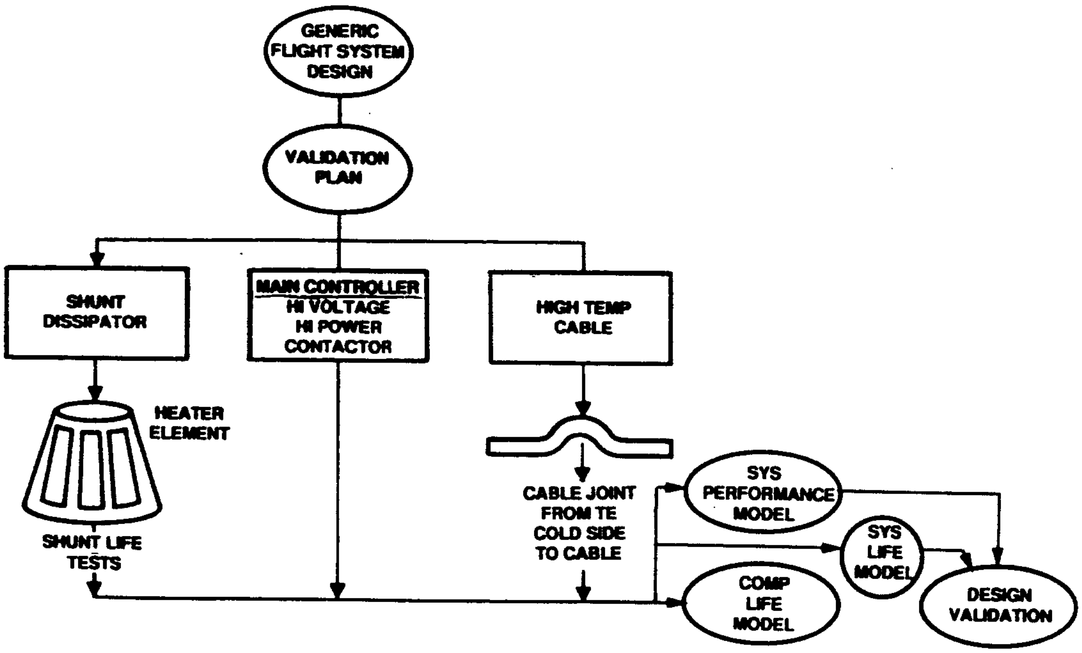


MAX STEADY-STATE POWER DISSIPATION = 1360 WATTS

2-8-89

JFM 6

JPL/LOS ALAMOS	PCC&D SUBSYSTEM COMPONENT DEVELOPMENT BLOCK DIAGRAM	



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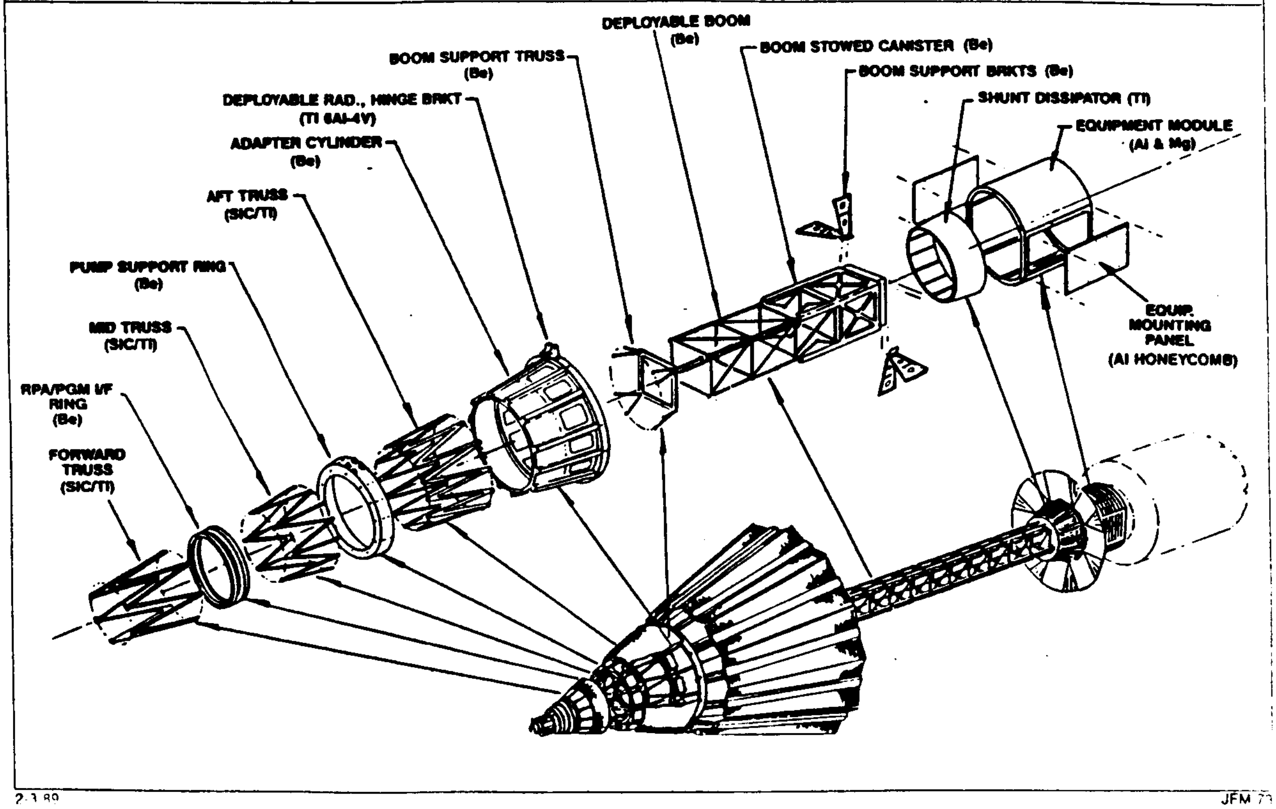
JPL/LOS ALAMOS	POWER CONDITIONING, CONTROL AND DISTRIBUTION SUBSYSTEM SUMMARY	

- USES PROVEN CONCEPTS AND DEVELOPMENT EXPERIENCE TO:
  - CONDITION, CONTROL AND DISTRIBUTE ELECTRICAL POWER TO THE MISSION MODULE AND INTERNAL SRPS COMPONENTS
  - ACCEPT POWER FROM MULTIPLE SOURCES:
    - MAIN THERMOELECTRIC CONVERTERS
    - ACL THERMOELECTRIC CONVERTER
    - GROUND POWER SUPPLY
    - LAUNCH VEHICLE/ORBIT TRANSFER STAGE
    - BATTERIES
  - PROVIDE TELEMETRY AND COMMAND INTERFACE WITH MISSION MODULE
- SUBSYSTEM DOCUMENTATION, INCLUDING PRELIMINARY CIRCUIT DESIGN AND ANALYSIS FOR KEY FUNCTIONAL COMPONENTS, SUPPORTS A HIGH CONFIDENCE IN THE SUBSYSTEM MASS PROJECTION
- DESIGN DETAILS HAVE BEEN PROVIDED TO SUPPPORT THE IDENTIFIED VALIDATION ITEMS
  - HIGH TEMPERATURE CABLE CONSTRUCTION
  - SHUNT DISSIPATOR ELEMENT
  - MAIN BUS LOAD CONTROLLER (HIGH VOLTAGE, HIGH POWER CONTACTOR)

2-8-89

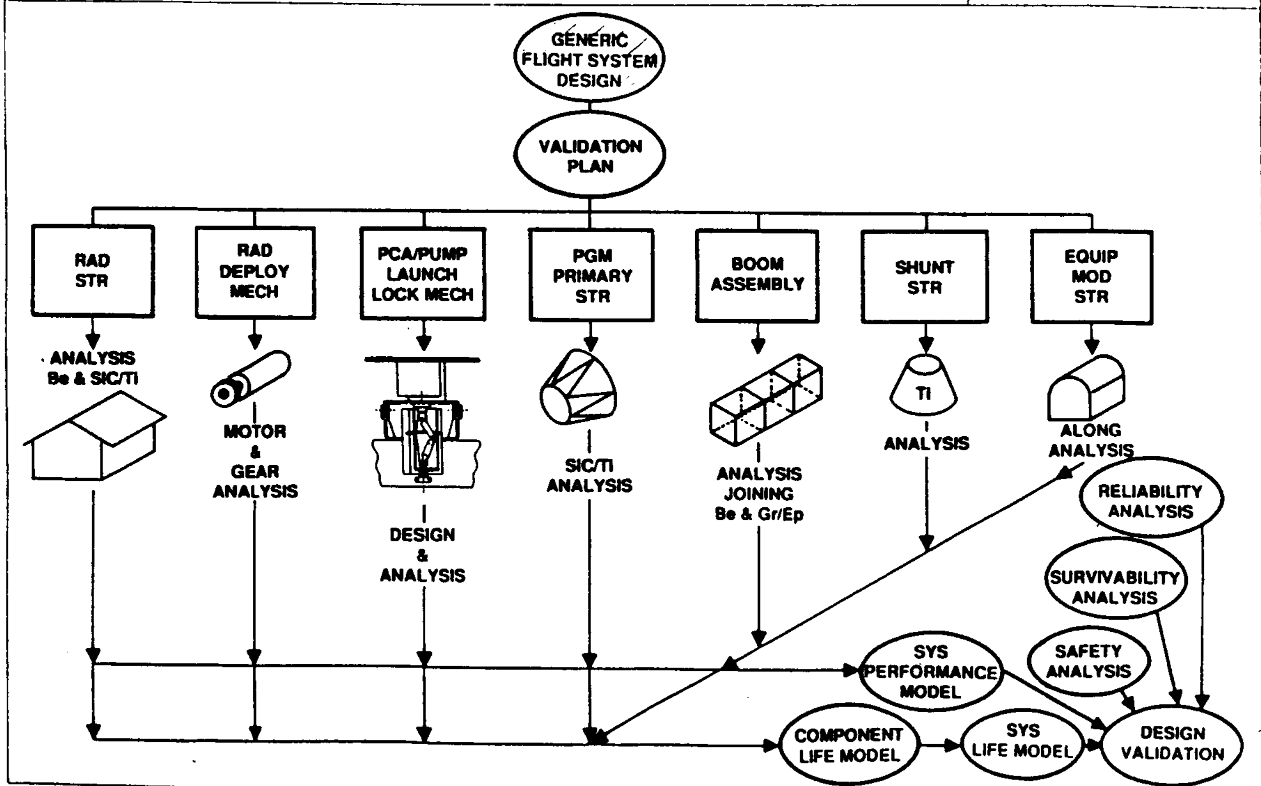
JFM 72

JPL/LOS ALAMOS	MECHANICAL/STRUCTURAL SUBSYSTEM M/S SS COMPONENTS	



2-3-89 JFM 73

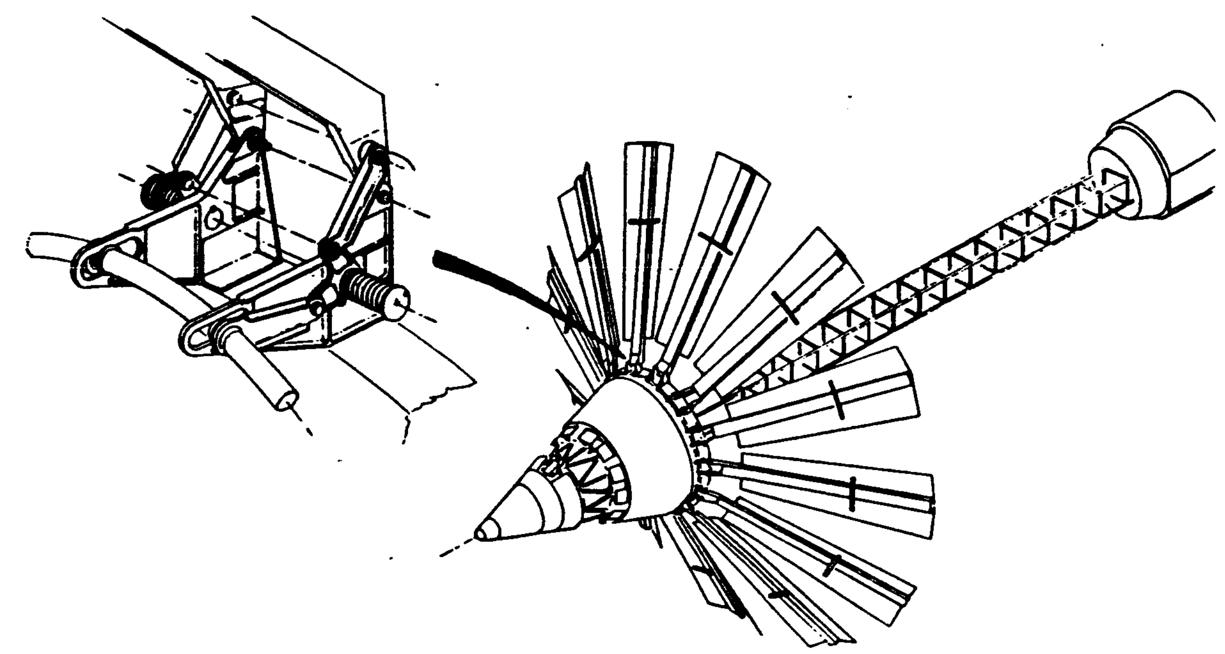
JPL/LOS ALAMOS	MECHANICAL/STRUCTURAL SUBSYSTEM COMPONENT DEVELOPMENT BLOCK DIAGRAM	



2-8-89 JFM 74

JPL/LOS ALAMOS

MECHANICAL/STRUCTURAL SUBSYSTEM RADIATOR PANEL DEPLOYMENT CONCEPT



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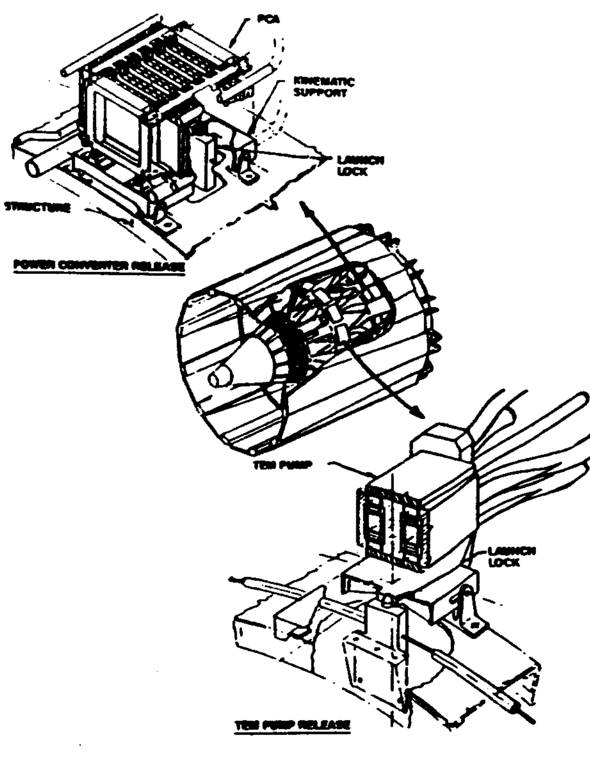
JFM-75

JPL/LOS ALAMOS

MECHANICAL/STRUCTURAL SUBSYSTEM COMPLAINT EQUIPMENT SUPPORTS



KEY REQUIREMENTS

- SUPPORT COMPONENT AND ADJACENT PIPING FOR LAUNCH CONDITIONS ($\pm$12 g's)
- PROVIDE FREE THERMAL EXPANSION

DESCRIPTION

- COMPONENTS LOCKED IN PLACE DURING LAUNCH
- LAUNCH LOCKS RELEASED UPON ORBITAL ACQUISITION

PERFORMANCE CHARACTERISTICS

- OVER-CENTER LATCH
- LATCH RELEASE ACTIVATED BY PIN PULLER
- TWO ACTUATORS RELEASE THIRTY COMPONENTS WHILE MAINTAINING AN 8:1 TORQUE MARGIN

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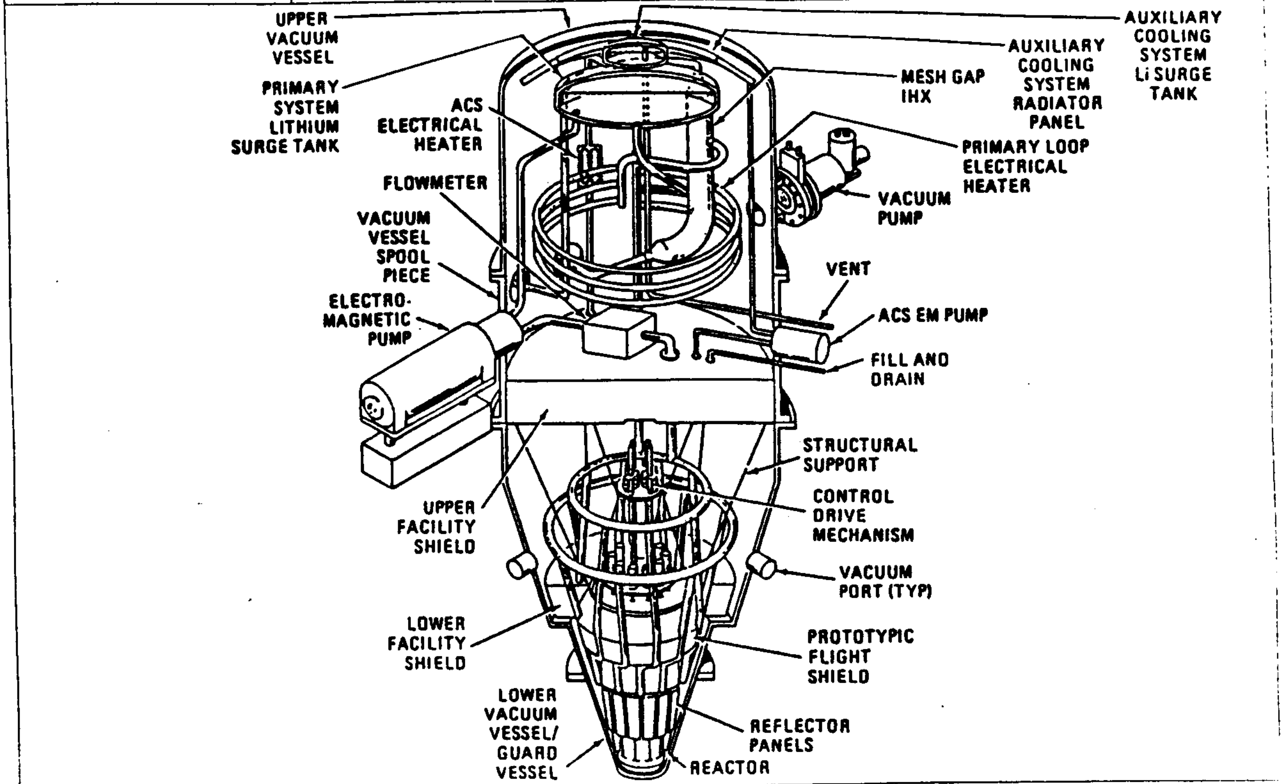
JFM-78

JPL/LOS ALAMOS

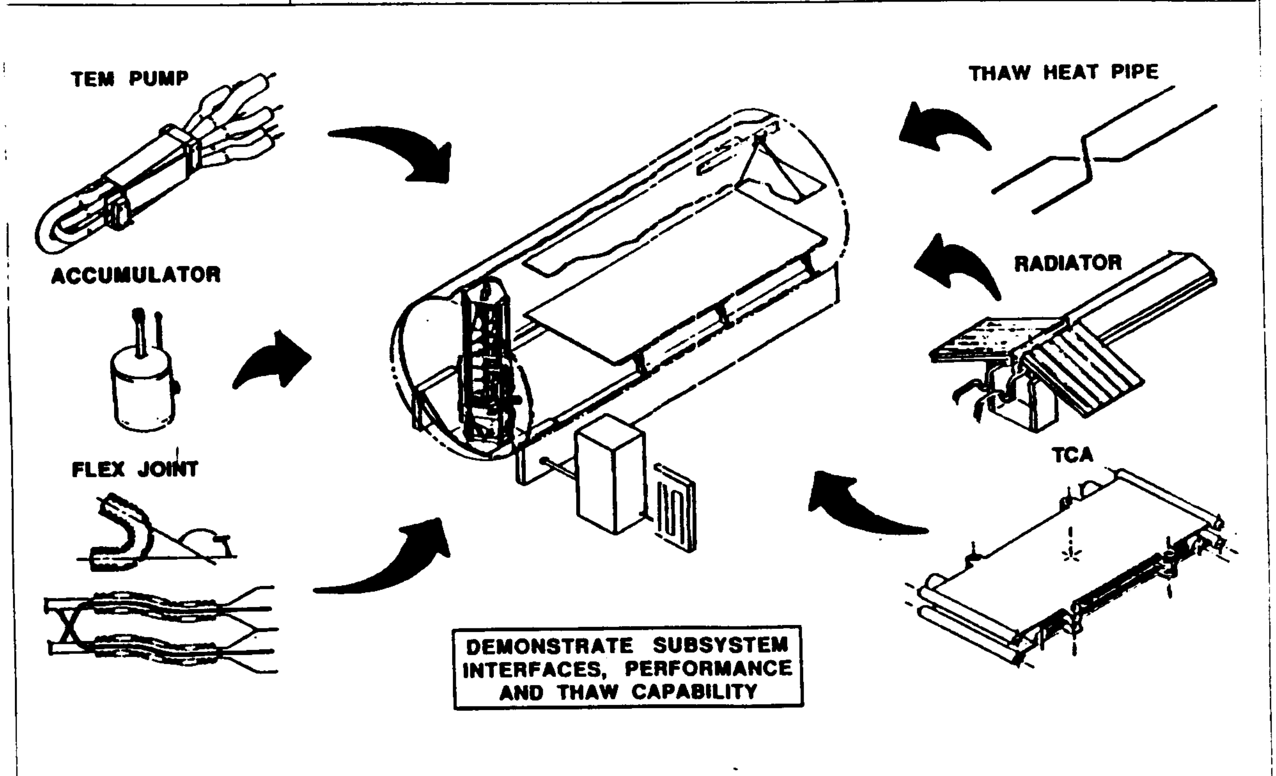
SP-100 NUCLEAR ASSEMBLY TEST (NAT)



2-8-89 JFM 8

JPL/LOS ALAMOS

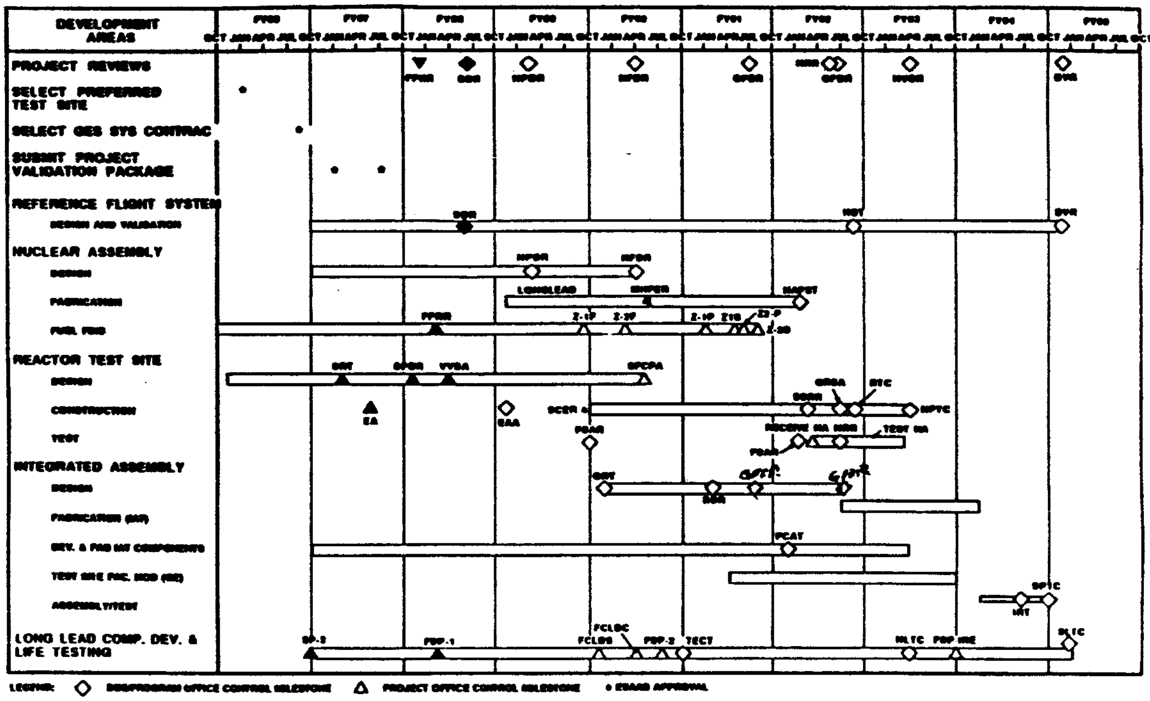
SP-100 INTEGRATED ASSEMBLY TEST (AIT)



2-8-89 JFM 82

JPL/LOS ALAMOS

SP-100 GES PROJECT MILESTONES SCHEDULE



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JFM-

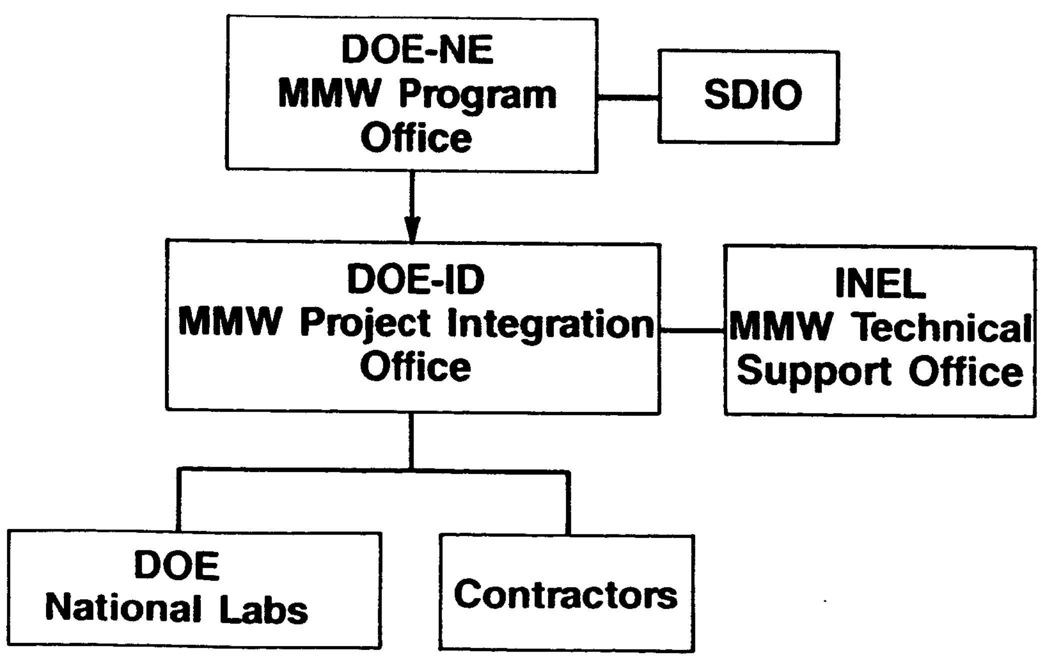
Multimegawatt Space Reactor Project

M.L. Stanley

Idaho National Engineering Laboratory

7-11217

MMW Space Reactor Project Organization



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MMW Space Reactor Project Mission

The multimegawatt space reactor project supports a mission area defined by SDIO as a need for safe, reliable, cost-effective electrical power in the multimegawatt range for use by space weapons and surveillance platforms.

mmw

Objective

To identify and develop at least one space nuclear system concept by the mid 90's that meets SDI requirements and for which feasibility issues have been resolved.

mmw

MMW Space Reactor Project Scope

- Total nuclear electrical power supply system from energy source through bus power conditioning
- Supporting technologies

mmw

Major Goals to be Accomplished by Mid 90's

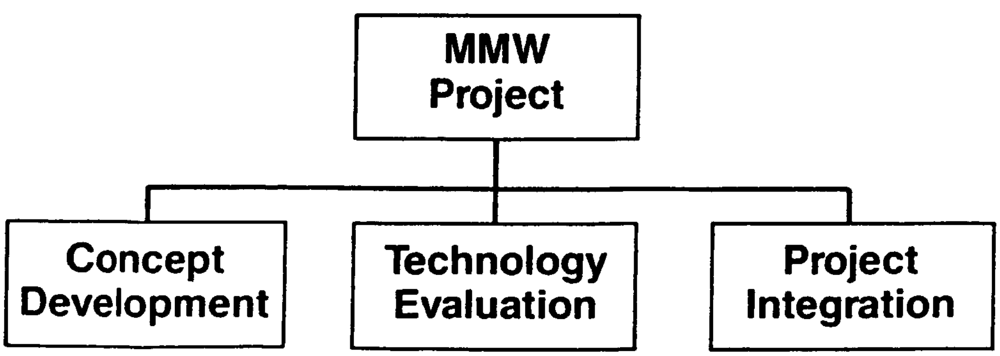
- Concept meets safety requirements
- Mass/volume compatible with available launch vehicles
- Minimum technical risk
- High reliability
- Flexible and scaleable
- Optimum life cycle cost

8 9099

MMW Space Reactor Project Strategy

- Phased concept down-selection
- Generic technologies development
- Integrate safety from start to finish

MMW Project Work Breakdown Structure



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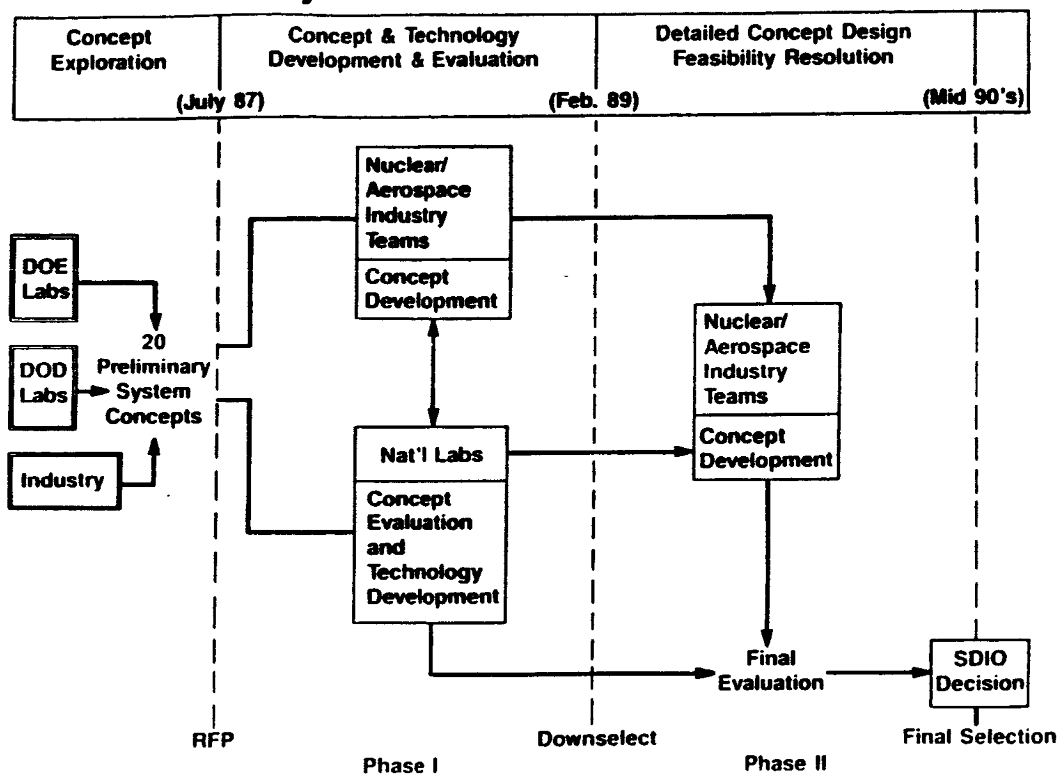
Project Schedule and Events



Power Systems Options

	Category I	Category II	Category III
Power Requirements	10's MWe	10's MWe	100's MWe
Operating Time	100's sec	100's sec +1 year of integ life	100's sec
Effluents	Yes	No	Yes or no
1 Orbit Recharge	No	Yes or continuous	No

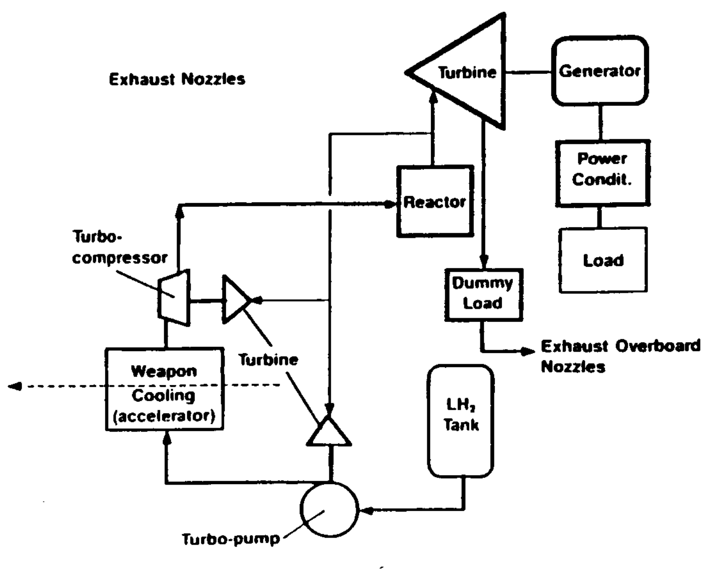
Concept Development Prime Contractors for Phase 1

Category I	Category II	Category III
Boeing	GA Technologies	Grumman
General Electric	Rockwell	
Westinghouse		

8-9102

Boeing/Rolls Royce Category 1 System

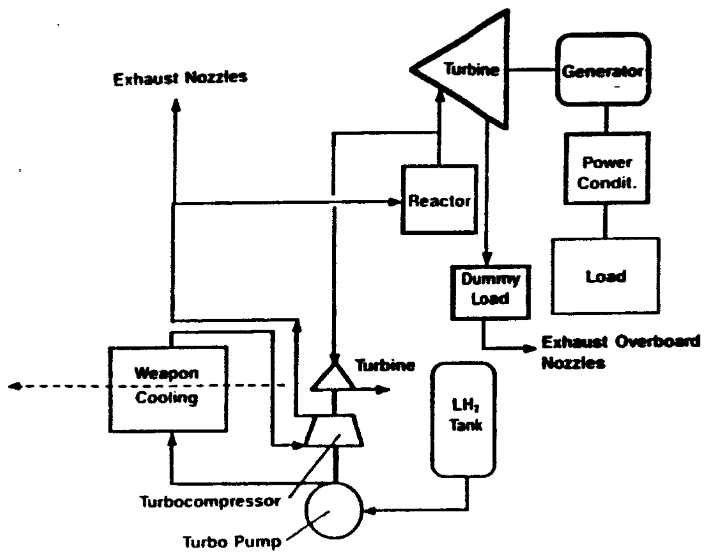
(Simplified Diagram)



Key Features

- Moderate fissile loading, fast reactor, pin fuel
- Two-pass core
- All H_2 available thru reactor
- Wound rotor generator, cryo cooled copper
- Integrated dummy load
- Turbo-compressor and Turbo-pump, separate turbines
- Growth potential

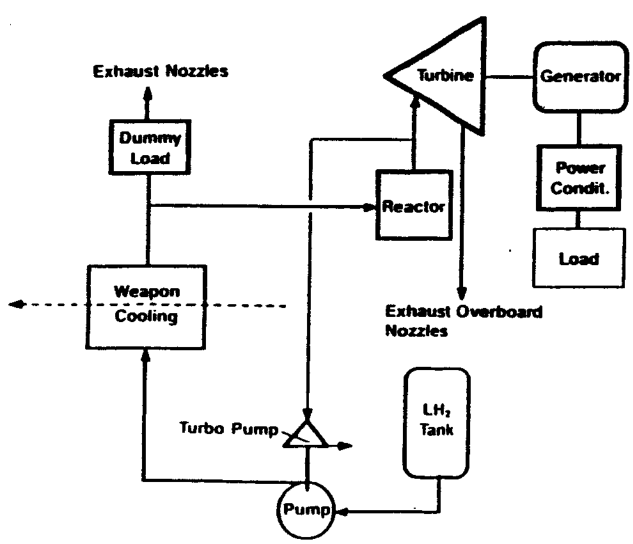
General Electric Company
Category 1 System
(Simplified Diagram)



Key Features

- Moderate fissile loading, fast Reactor, cermet fuel
- Superconducting generator rotor
- Integrated dummy Load
- Turbo-compressor/Turbo-pump same shaft and turbine
- Good growth potential

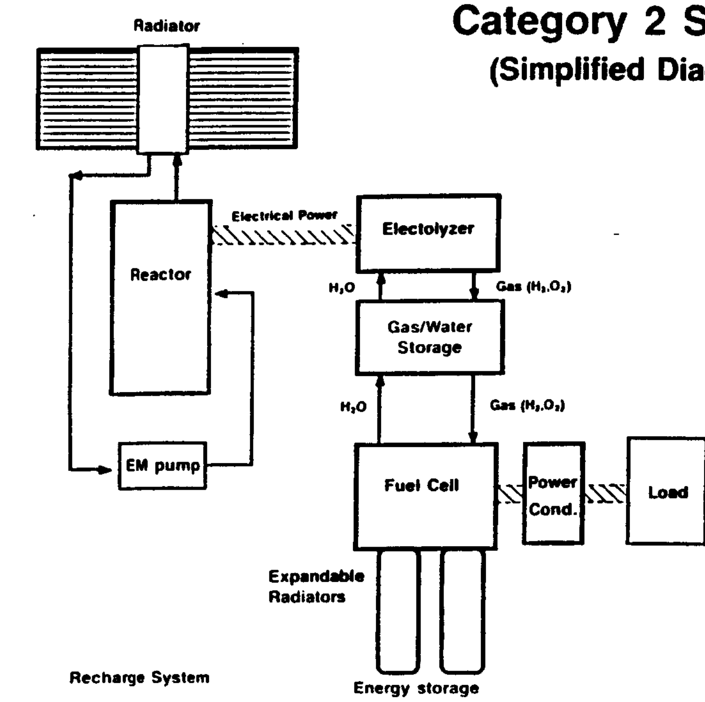
Westinghouse/McDonnell Douglas
Category 1 System
(Simplified Diagram)



Key Features

- Low fissile loading, thermal
- Hyper-conducting generator
- Integrated dummy load
- Good growth potential

General Atomics Category 2 System
(Simplified Diagram)



Key Features

- **Thermionic reactor (fast), high fissile loading**
- **Heat pipe radiators on reactor system**
- **Alkaline fuel cell for burst power**
- **Expandable radiator on fuel cell**

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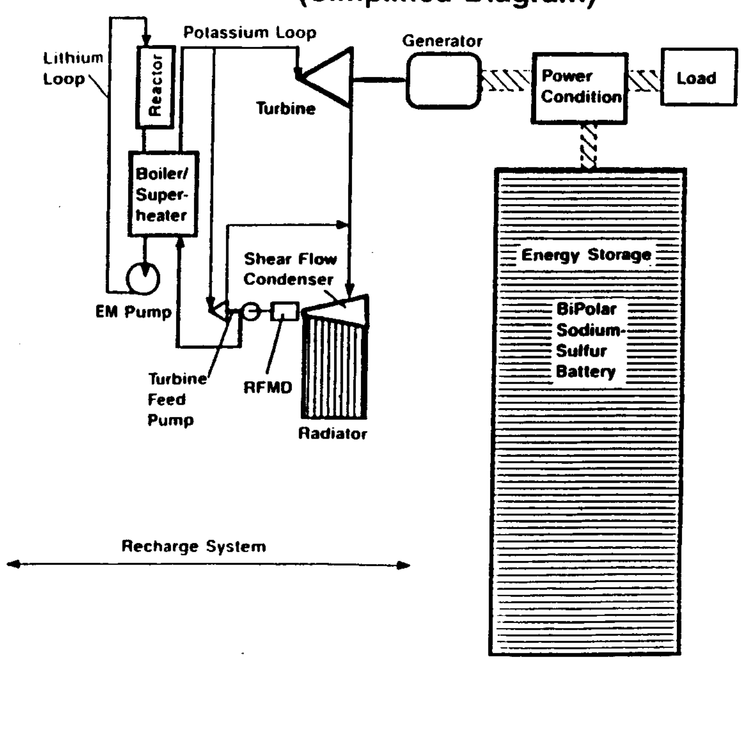
Rockwell International Category 2 System
(Simplified Diagram)

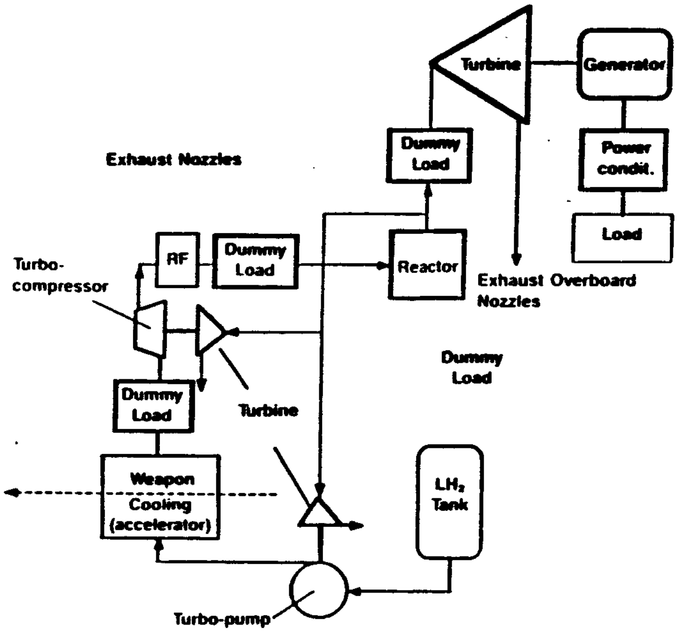


Key Features

- **Fast reactor, moderate fissile loading, cermet fuel**
- **Reheat potassium cycle**
- **Shear flow condenser**
- **Heat pipe radiator**
- **Homopolar induction alternator**
- **Recharge system provised portion of burst power**
- **Thermal storage for power conditioning, steam & expandable radiators**
- **Batteries cooled by direct radiation**

Grumman/B&W Category 3

(Simplified Diagram)



Key Features

- Low fissile loading, thermal reactor, particle fueld, H_2O moderated
- All H_2 available thru reactor
- Unique high Hz generator
- Three integrated dummy loads
- Turbo-compressor and Turbo-pump, separate turbines
- Growth and down scale potential

Specific Concept Technical Issues

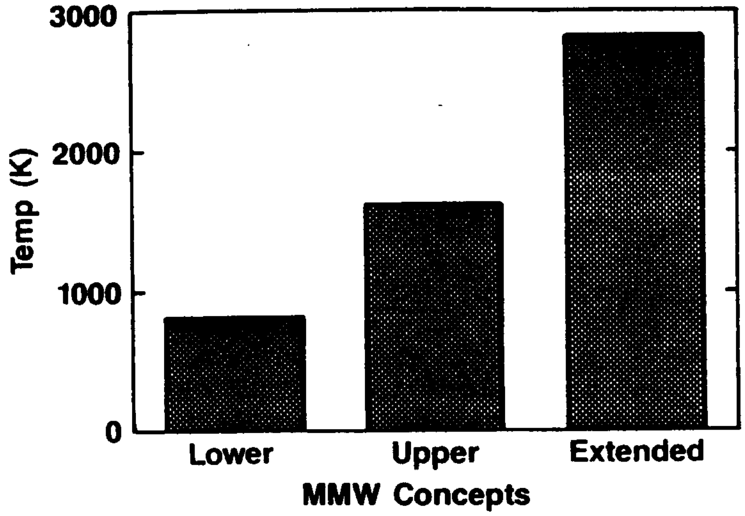
- Fuel integrity and performance
- Conversion efficiency and reliability
- Reactor and power system control
- Material/coolant compatibility
- Waste heat acquisition, transport, and rejection
- Two-phase fluid transport

All technical issue resolution is used to aid in concept evaluation

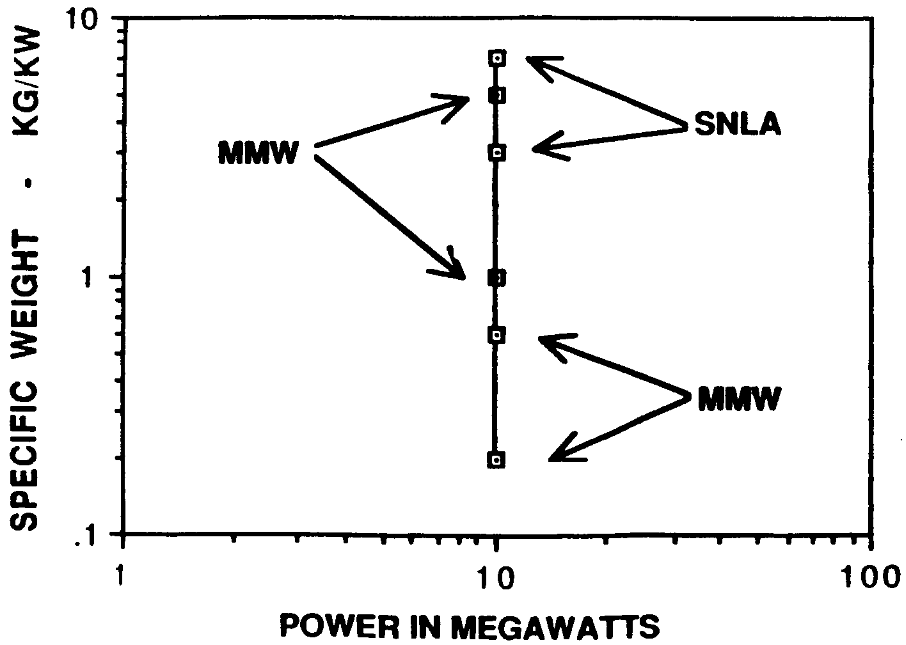
- Safety
- Reliability
- Mass/volume
- Operations
- Developmental risk
- Life cycle cost

8 9105

Outlet Temperature Range

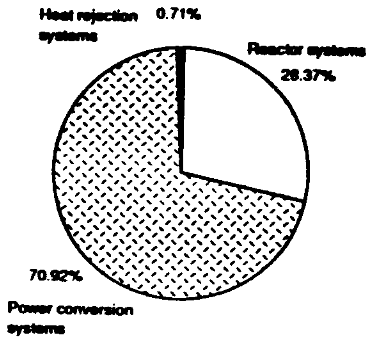


SPECIFIC WEIGHT VS POWER



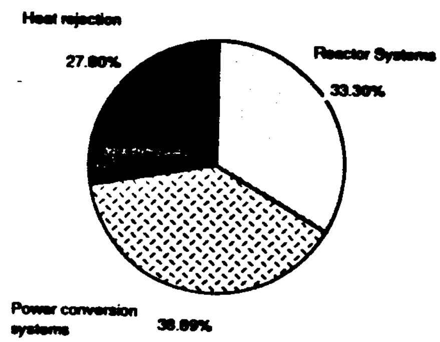
Typical Open Cycle System

w/o power conditioning and working fluid
specific weight ~ 0.2 kg/kWe



Typical Closed Cycle

Specific weight ~3.8 kg/kWe



MMW POWER CONCEPTS

COMPANY	REACTOR	POWER CONVERSION	POWER	MAIN RADIATOR
Boeing	Pin-Type, fast reactor, H_2-Cooled	Open-cycle turbo-gen.	10's MWe burst	None, effluents o.k.
Gen. Elect.	Cermet-fuel, fast reactor H_2-cooled	"	"	"
Westinghouse	NERVA derivative, fast reactor, H_2-cooled	"	"	"
Gen. Atomic	Incore thermionic fast reactor, Li-cooled	Closed thermionic + alkaline fuel cells	10's MWe burst + steady state	Heat pipes, no effluents
Rockwell	Cermet-fuel, fast reactor Li-cooled.	Closed Rankine + NaS batteries	"	"
Grumman	Particle bed, thermal reactor, H_2-cooled	Open-cycle turbo-gen.	100's MWe burst	None, effluents o.k.

INEL

mmw

MATERIAL ENVIRONMENTS

REACTOR	COOLANT	SYSTEM MATERIALS
LMFBR	Na @ 900K	Stainless steels
HTGR	He @ 1100K	Superalloys
SP-100	Li @ 1350K	Niobium alloy

MMW:

Cermet	Li @ 1600K	• Refractory metal alloys?
PBR	H_2 @ 1350K	• Ceramics?
NERVA	H_2 @ 1200K	• CC composites?
Thermionic	NaK or Li @ 1300K	• Metal fiber/metal matrix?

HIGHER TEMP. -------> GREATER EFFICIENCY, LESS WEIGHT!

INEL

mmw

REACTOR FUEL CONCEPTS

REACTOR CONCEPTS	LIKELY FUEL (Fuel Temp. & Coolant)	PRIMARY ISSUES
LIQ-METAL-COOLED		
• Incore Thermionic	UO_2 pellets in W-Hf emitter (2800K, Li or NaK)	Fabrication, materials compatibility, temp. & irrad. effects on mech. properties and TI performance.
• Cermet Core	UN in W-Re matrix (1730K, Li)	Fabrication, effects of cladding failure, irrad. effects on mech. properties.
GAS-COOLED		
• Particle Bed	ZrC-coated UC_2 particles (1350K, H_2)	Fuel behavior under prototypical operating conditions, e.g. particle strength, bed vibration & compaction, flow distribution.
• Pin-type	UC pins in Mo & SS cladding (1850K, H_2)	Fabrication, fuel/clad compatibility, effects of power cycling.
• 710 Derivative	UO_2-W cermet (1900K, H_2)	Temp. & irrad. effects on mech. properties; chemical stability.
• NERVA Derivative	ZrC-coated UC_2 particles in C matrix (1300K, H_2)	Fuel particle size.

INEL

Technology Working Groups Formed to Assist in Defining and Evaluating Feasibility Issues and in Planning Project Tasks

Fuels	Materials	Thermal Management	I & C	Energy Storage
PNL	ORNL	LANL	SNLA	ORNL
WHC	NASA	NASA	NASA	NASA
ORNL	AFWAL	AFAL	AFWAL	AFWAL
LANL	IDA	AFWAL	ANL	SNLA
INEL	INEL	PNL	ORNL	INEL
		INEL	INEL	

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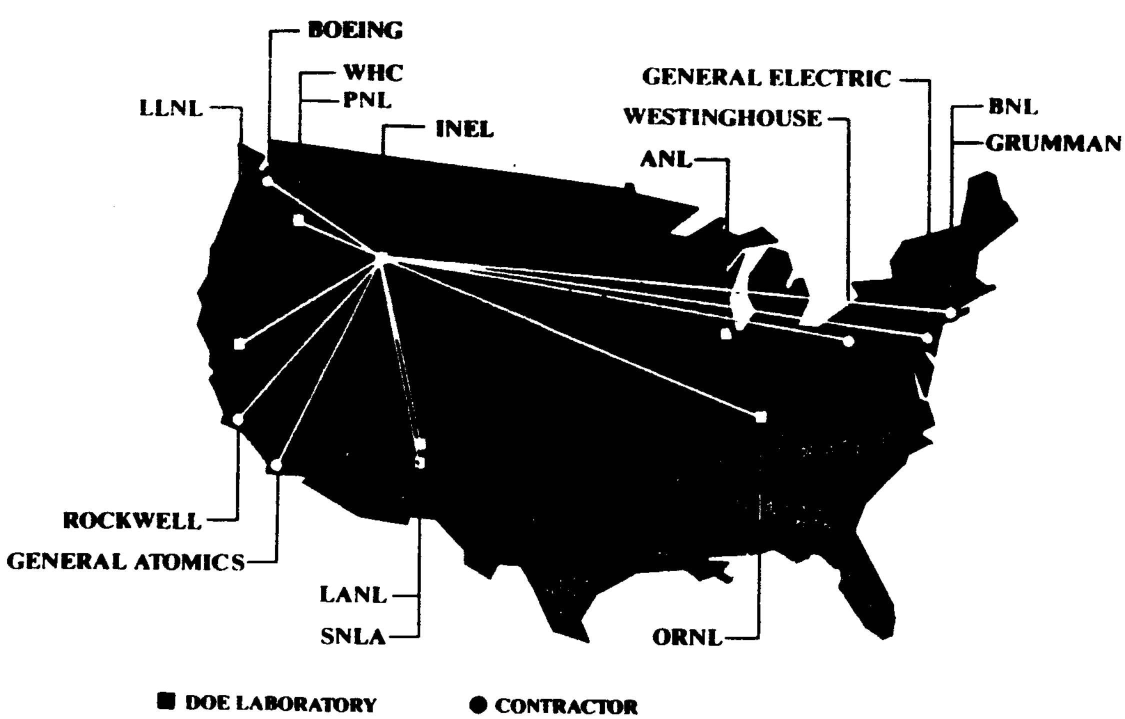
MMW PARTICIPANTS



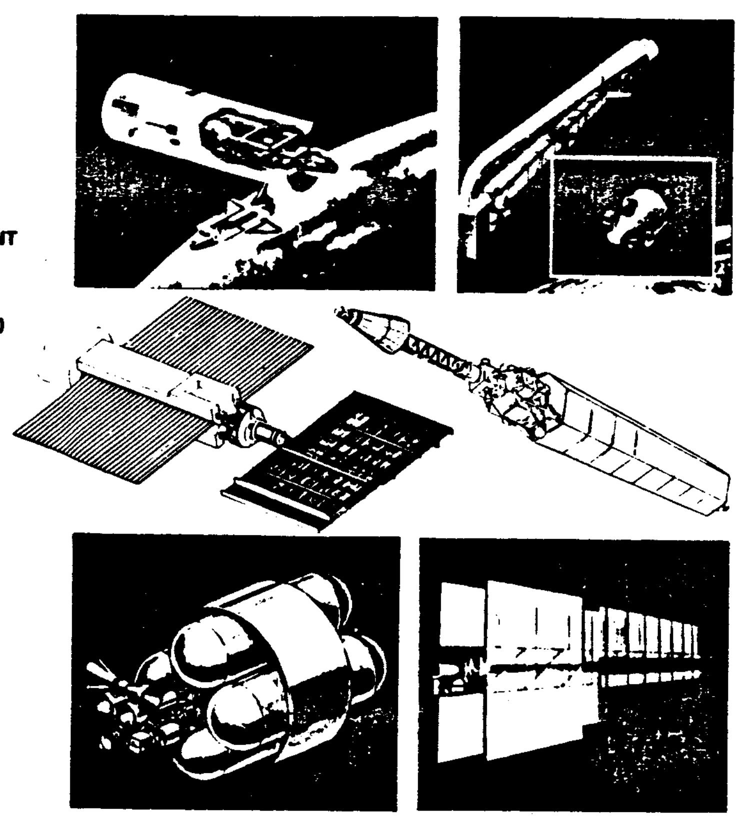
mmw

MMW Space Reactor Project Summary

- Joint SDIO/DOE Sponsorship
- Establish conceptual designs for three categories of power system
- Resolve feasibility issues by mid 90's
- Stress "Safe Systems"

8-9122

MULTIMEGAWATT (MMW) SPACE REACTOR PROGRAM



MULTIMEGAWATT (MMW) SPACE REACTOR PROGRAM

- A SPACE REACTOR DEVELOPMENT PROGRAM FOR POWER LEVELS BEYOND SP-100
  - BURST (10'S TO 100'S OF MWE)
  - CONTINUOUS (10'S OF MWE)
- WILL SUPPORT SPACE APPLICATIONS IN THE LATE 1990'S AND THE 21ST CENTURY
  - SDI (FIRST APPLICATIONS)
  - FAR-TERM CIVIL APPLICATIONS
- CURRENTLY A JOINT SDIO/DOE PROGRAM

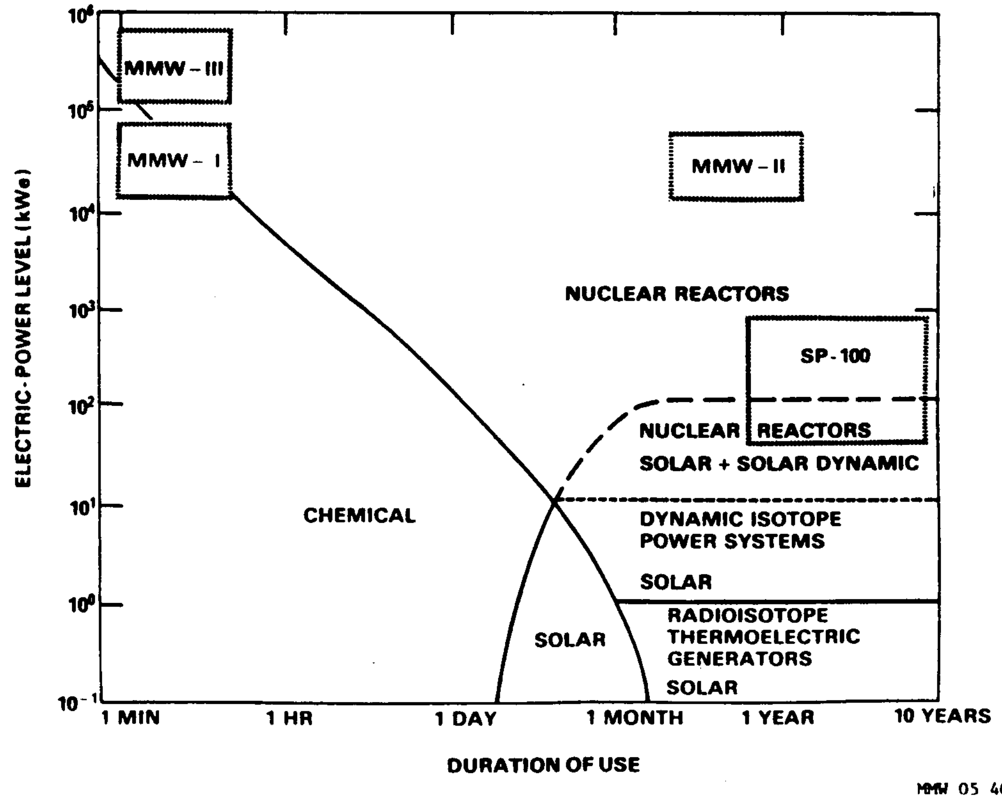
MMW 03 103

MULTIMEGAWATT (MMW) SPACE REACTOR PROGRAM

PROGRAM NEED

- POTENTIAL SDI APPLICATIONS INCLUDE:
  - NEUTRAL PARTICLE BEAM (NPB) WEAPON
  - NPB DISCRIMINATOR
  - FREE ELECTRON LASER
  - ELECTROMAGNETIC LAUNCHER
  - MMW ORBITAL TRANSFER VEHICLE (OTV)
- POTENTIAL FAR-TERM CIVIL APPLICATIONS:
  - HIGH POWERED PROPULSION UNITS FOR INTERPLANETARY EXPLORATION & TRAVEL
  - MMW OTVs
  - ADVANCED LUNAR AND PLANETARY BASES
  - ENERGY INTENSIVE SPACE BASED INDUSTRIAL APPLICATIONS

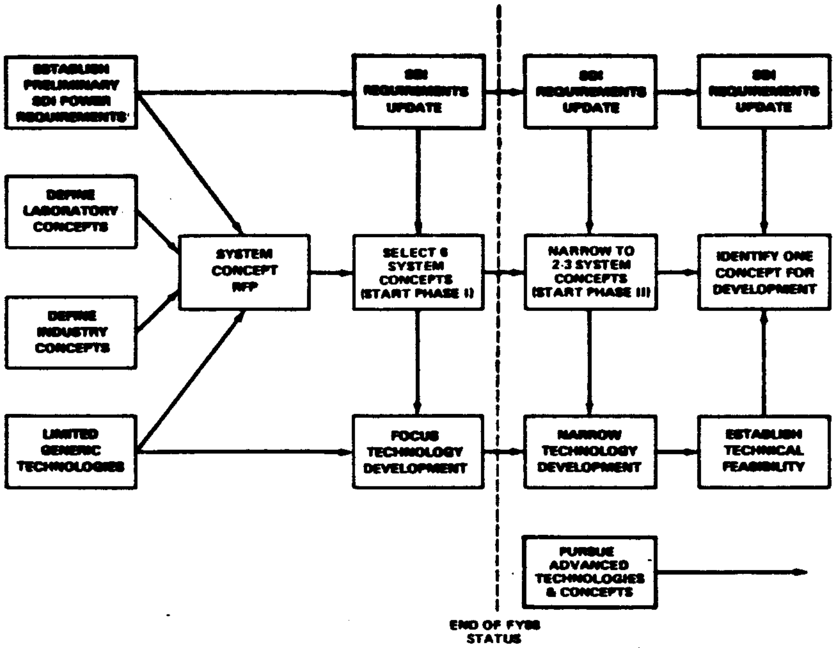
REGIMES OF POSSIBLE SPACE POWER APPLICABILITY



MMW 05 403

MULTIMEGAWATT (MMW)
SPACE REACTOR PROGRAM

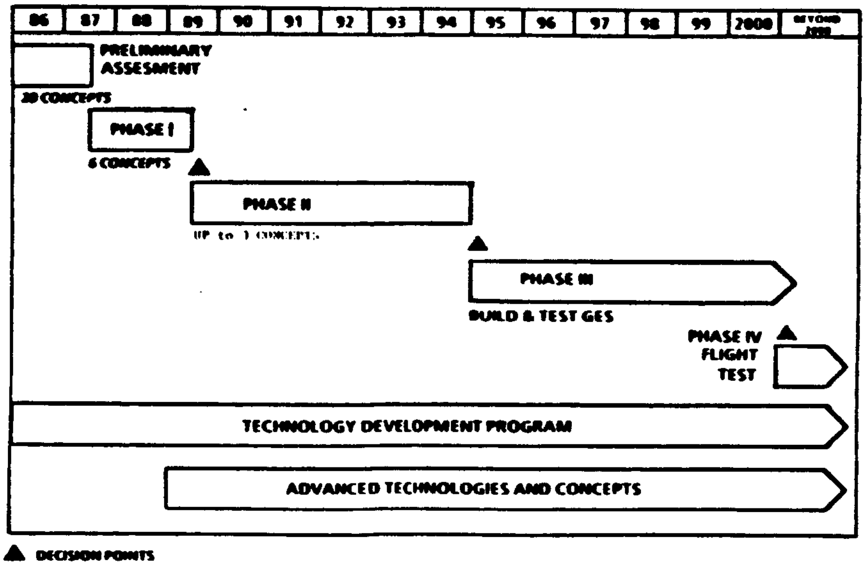
MMW SPACE REACTOR DEVELOPMENT APPROACH FOR PHASES I & II



MMW 03 200

MULTIMEGAWATT (MMW) SPACE REACTOR PROGRAM

LONG RANGE PLAN



MULTIMEGAWATT (MMW)
SPACE REACTOR PROGRAM
PHASE I TASKS -- 10 MONTHS (FY 88-89)

1. PRELIMINARY SYSTEM ENGINEERING & TRADEOFF STUDIES
2. SYSTEM ANALYSIS TO CHARACTERIZE PERFORMANCE
3. PRELIMINARY DRAWINGS & LAYOUT PLANS
4. IDENTIFY TECHNOLOGY FEASIBILITY ISSUES
5. ASSESSMENT OF SCALABILITY
6. OUTLINE OF PRELIMINARY SAFETY ASSESSMENT
7. PHASE II PLAN

DOWN SELECTION TO 2 OR 3 CONCEPTS AND BEGIN PHASE II ACTIVITIES

PV14

JW 0912

PHASE II TASKS

1. PRELIMINARY SAFETY ASSESSMENT
2. COMPLETE R&D TO RESOLVE PHASE I FEASIBILITY ISSUES
3. DETAILED SYSTEM ENGINEERING & TRADEOFF STUDIES, WITH SPECIFIC COMPONENT SELECTION & DETAILED DRAWINGS, ANALYSIS, AND LAYOUT PLANS
4. CONCEPT LIFE CYCLE COST
5. ENGINEERING DEVELOPMENT PROGRAM PLAN FOR FINAL DESIGN
6. PRELIMINARY GROUND ENGINEERING SYSTEM TEST CONFIGURATION AND TEST PROGRAM OUTLINE

APPENDICES

1. Historical Overview of the United States Use of Space Nuclear Power
2. Agenda
3. List of Attendees

IAF-ICOSP89-9-1

HISTORICAL OVERVIEW OF THE UNITED STATES USE OF SPACE NUCLEAR POWER

Gary L. Bennett
National Aeronautics and Space Administration
Propulsion, Power and Energy Division
Washington, D. C. 20546

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Author running head: G. L. Bennett

Title running head: SPACE NUCLEAR POWER

Address all correspondence to: Dr. Gary L. Bennett
National Aeronautics and Space Administration
Code RP
Washington, D. C. 20546

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HISTORICAL OVERVIEW OF THE UNITED STATES USE OF SPACE NUCLEAR POWER

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ABSTRACT

Since 1961, the United States has successfully flown 35 space nuclear power sources on 20 space systems. These space systems have included the Apollo, Pioneer, Viking, and Voyager spacecraft launched by the National Aeronautics and Space Administration and navigation and communications satellites launched by the Department of Defense. These power sources performed as planned and in many cases exceeded their power requirements and/or lifetimes. All of the power sources met their safety requirements. This paper surveys past uses of space nuclear power in the U. S. and thus serves as an historical framework for other papers in this Conference dealing with future U. S. applications of space nuclear power.

INTRODUCTION

The United States has used nuclear power on a number of technically sophisticated space systems which have greatly advanced our understanding of the solar system. In many cases, nuclear power was the only way to accomplish these missions.

In the early 1950s, the U. S. began studies of the use of nuclear power on spacecraft and by the late 1950s had active programs under way to develop both radioisotope and reactor power sources for spacecraft. The first actual use of a nuclear power source (NPS) on a spacecraft came in 1961 with the launch of the small SNAP-3B* radioisotope thermoelectric generator (RTG). In total, as shown in Table 1, the U. S. has launched 38 RTGs and one reactor to provide power for 23 space systems. (35 of these NPS on 20 space systems are still in space or on other planetary bodies.) The U. S. has also used small radioisotope heater units (RHUs) on some of its RTG-powered science missions and on the Apollo 11 science package. All of the U.S. RTGs have used ^{238}Pu as the source of heat because of its long half-life (87.8 years) and its comparatively low level of radiation emission. The only U. S. space reactor flown used ^{235}U as the fuel.[1,2]

Initially these NPS were used to supplement solar power sources but gradually with the improvement of NPS technology and with the ever increasing requirements of spacecraft power (particularly for outer planet missions) NPS became the sole source of power. In a sense this was inevitable given the compact size, self-sufficiency, reliability, survivability, long lifetimes and operational flexibility of NPS.

The basic NPS consists of a heat source (either a naturally decaying radioisotope or a nuclear reactor) and a converter (e.g., thermoelectric, thermionic, Brayton, Rankine, Stirling, magnetohydrodynamic) to change the thermal power into electrical power. To date the U. S. has only used thermoelectric converters because of their proven reliability and the lack of a requirement to provide powers high enough to warrant the use of more

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*SNAP is an acronym for Systems for Nuclear Auxiliary Power. All odd-numbered SNAP power sources used radioisotope fuel and all even-numbered SNAP power sources used nuclear fission reactors.

efficient conversion systems such as turbine/alternators.

The following sections provide an overview of the NPS flown by the U. S. This overview will serve to provide the framework for understanding the current programs under way in the U. S. Throughout the evolution of the U. S. space NPS program there has been a general technology trend to improve NPS performance, efficiency, and specific power. This trend has led to improvements in the fuel and in the technology of thermoelectric materials, from the lead telluride (PbTe) used in the first five RTG concepts flown to the silicon germanium (SiGe) used in the SNAP-10A reactor and in the multi-hundred watt (MHW) RTGs and planned for use in future NPS. The performance of these NPS has clearly demonstrated that they can be safely and reliably engineered to meet a variety of space-mission requirements.[2]

RADIOISOTOPE POWER SOURCES

The first SNAP, known as SNAP-1, was to use a radioisotope heat source coupled to a mercury Rankine cycle turbine/alternator. However, evolving requirements led the U. S. toward the use of thermoelectrics such as were used on the SNAP-3B RTGs shown in Figure 1. For this paper the various RTGs have been grouped into six basic design concepts: SNAP-3B, SNAP-9A, SNAP-19, SNAP-27, TRANSIT-RTG, and MHW-RTG. Since the focus of this paper is on providing a general historical overview the detailed power performance, which has been summarized in Reference 2, will not be repeated here.

SNAP-3B

The SNAP-3B RTGs, which were developed out of the SNAP-3 program, were used to provide 2.7-We of power to radio transmitters and other electronic equipment aboard the U. S. Navy's Transit 4A and Transit

4B navigation satellites. The SNAP-3B RTGs also were flown to prove the practicability of radioisotope power sources in space.[2,3]

Prior to the use of NPS, continuous electrical power had been obtained by solar arrays and nickel-cadmium (NiCd) batteries. Concern over possible degradation of solar cells in the inner Van Allen belt and battery breakdown from repeated charge-discharge cycles had led the Navy to fly RTGs.[3]

Each 2.1-kg SNAP-3B RTG contained 27 spring-loaded, series-connected pairs of PbTe thermoelectric elements operating at a hot junction temperature of about 783 K and a cold-junction temperature of about 366 K. Each radioisotope heat source provided about 52.5 Wt. The design life was 5 years. Figure 2 shows an assembled SNAP-3B and Figure 3 shows the first mounting of a NPS to a spacecraft in 1961. At the time Transit 4A, which is shown in Figure 4, had the longest operating life of any satellite launched by the U. S. -- over 15 years. The RTG on Transit 4B was still operating 10 years after launch when the last signals were received.[2,3,4,5]

SNAP-9A

The SNAP-9A RTGs, as shown in Figures 5 and 6, were built to provide all of the electrical power for the Navy Transit 5BN navigation satellites. In fact, Transit 5BN-1, which was launched in 1963 and is shown in Figure 7, was the first satellite to get all of its power from an RTG. The RTG approach was selected because RTGs are inherently radiation resistant, whereas the solar-cell power system of Transit 4B had been adversely affected by a 1962 high-altitude nuclear explosion.[6] Each 12.3-kg SNAP-9A was designed to provide 25 We at a nominal 6 V for 5 years in space after 1 year of storage on Earth.[7]

One of the objectives of the Transit 5BN program was to demonstrate the satisfactory operation and long-life potential of the SNAP-9A power supply. The Applied Physics Laboratory, which built the satellites, reported that the objective was fully satisfied. In fact, Transit "5BN-1 demonstrated the extreme simplicity with which thermoelectric generators may be integrated into the design, not only to provide the electrical power but also to aid in thermal control".[4] Some waste heat from the RTG was used to maintain electronic instruments within the satellite at a temperature near 293 K.

SNAP-19

The SNAP-19 technology-improvement program built on the SNAP-9A development program, with the SNAP-19B power source specifically designed for use on NASA's Nimbus weather satellites. The Nimbus SNAP-19 program was the first demonstration of RTG technology aboard a NASA spacecraft, and, as such, it developed the data and experience to support interplanetary missions using RTGs. Subsequent modifications were made in the SNAP-19B design to power NASA's Pioneer and Viking missions. The Viking SNAP-19 is shown schematically in Figure 8.

For Nimbus III, two 13.4-kg SNAP-19B RTGs were mounted on the spacecraft platform as shown in Figure 9 to provide a total of 56.4 We at beginning of mission (BOM) to augment the solar power source. During the design lifetime of one year, nuclear power comprised about 20 percent of the total power delivered to the regulated power bus, allowing a number of extremely important atmospheric-sounder experiments to operate in a full-time duty cycle. Without the RTGs the total delivered power would have fallen below the load line about 2 weeks into the mission.[8,9]

Additional improvements were made leading to the SNAP-19s which were built for the Pioneer 10 and 11 spacecraft, the first to fly by Jupiter and Saturn. Figure 10 is an artist's rendition of a Pioneer spacecraft flying past Jupiter. The four RTGs on each Pioneer spacecraft provided over 160 We at BOM. The Pioneer RTGs performed so well that Pioneer 11 was retargeted for a flyby of Saturn.[10] Both spacecraft are still operating 16 to 17 years after their launches, well beyond their 3-year design life requirement, and are providing valuable information about the heliosphere. Pioneer 10 is presently the most distant man-made object, having traveled beyond the orbit of Pluto, the outermost known planet.[11] The spacecraft should have sufficient power to provide useful data through at least 1996.[12]

The SNAP-19 design was further modified for the Viking Mars Landers to accommodate high-temperature (400 K) sterilization, storage during the spacecraft's cruise to Mars, and, on the surface of Mars, the thermal cycling caused by the rapid and extreme temperature changes of the Martian day-night cycle. As shown in Figure 11 each Viking Lander carried two of the 15.2-kg RTGs which produced a total power of over 85 We at BOM. The RTGs were to produce a total of 70 We for the primary mission of 90 days on the surface of Mars. All four RTGs met the 90-day requirement and they were still operating 4 to 6 years later when the Landers were separately and inadvertently shutdown on commands from Earth.[13,14] Based on their power performance, it had been estimated that the RTGs on Viking Lander 1 were capable of providing sufficient power for operation until 1994 -- 18 years beyond the mission requirement.[15]

Both the Pioneer and Viking RTGs demonstrated the operability and usefulness of RTGs in interplanetary spacecraft. All of these RTGs performed beyond their mission requirements.

SNAP-27

The SNAP-27 RTGs were developed to power the experiments of

NASA's Apollo Lunar Surface Experiments Package (ALSEP). The RTG design requirement was to provide at least 63.5 We at 16 V DC one year after lunar emplacement. (In the case of Apollo 17, the requirement was 69 We two years after emplacement.) The use of RTGs to power the ALSEPs was a natural choice because of their light weight, reliability, and ability to produce full electrical power during the long lunar night-day cycle. Since the ALSEPs were to be manually positioned by the astronauts, the RTG designers took advantage of this assembly capability. The converter and the sealed-fuel-capsule assembly were kept separately in the Lunar Module and integrated on the Moon as shown in Figure 12. This approach allowed optimization of the electrical, mechanical, and thermal interfaces of the two major hardware subsystems of the RTG.[16] Figure 13 is a schematic of the SNAP-27 RTG.

A total of five RTG-powered ALSEPs were placed on the Moon. In each case the RTGs exceeded their mission requirements in both power and lifetime (all were still operating when NASA shut down the stations on 30 September 1977). Through this performance beyond mission requirements, the SNAP-27 RTGs enabled the ALSEP stations to gather long-term scientific data on the internal structure and composition of the Moon, the composition of the lunar atmosphere, the state of the lunar interior, and the genesis of lunar features.[17]

TRANSIT RTG

The TRANSIT RTG was developed specifically as the primary power for the TRIAD navigational satellite, with auxiliary power to be provided by four solar-cell panels and one 6-Ah NiCd battery. The 13.6-kg TRANSIT RTG, shown in Figure 14, was a modular RTG with a 12-sided converter surrounding the radioisotope heat source. The low hot side temperature (673 K) allowed operation of the PbTe thermoelectric elements in a vacuum.[18]

To accomplish its mission of improving the accuracy of orbital determinations the TRIAD spacecraft was designed with three ("triad") main units as shown in Figure 15. These units are the power unit, the disturbance compensation system (DISCOS), and the main electronics unit. The TRANSIT RTG was the primary power source in the power unit.

DISCOS, which was located at the satellite's center of mass, was designed to minimize the effects of aerodynamic drag forces and solar radiation pressure experienced in lower altitude orbits. DISCOS performed very successfully leading to the provision of excellent navigational capabilities to a wider variety of users. In addition, TRANSIT TRIAD provided very important measurements of the Earth's magnetic field. TRANSIT TRIAD operated for over 13 years -- well beyond the design requirement of 5 years.

Multihundred Watt (MHW) RTG

The designs of the Lincoln Experimental Satellites 8 and 9 (LES 8/9) and NASA's Voyager 1 and 2 spacecraft led to a doubling of the power requirement compared to the SNAP-27 RTGs. The MHW-RTG, which is illustrated in Figure 16, was designed to produce over 150 We at BOM. Two MHW-RTGs were flown on each LES as shown in Figure 17 and three MHW-RTGs were flown on each Voyager as shown in Figure 18. Originally, Voyagers 1 and 2 were to fly past Jupiter and Saturn.

The MHW-RTGs were the first U. S. space RTGs to use SiGe as the thermoelectric material (see Figure 19). The use of SiGe permitted higher operating temperatures and higher specific powers all within a space vacuum operating environment.[19]

The MHW-RTGs on LES 8/9 continue to operate beyond the prelaunch required five-year operational life. Similarly, the MHW-RTGs on Voyagers 1/2 continue to operate well beyond the prelaunch required four-year operational life. Because of the outstanding performance of the Voyager RTGs NASA was able to extend the Voyager mission to include flybys of Uranus and Neptune.[20] The RTGs are performing so well that scientific data will be received into the early 21st century.[12]

The successful performance of the MHW-RTGs has led to the use of the SiGe technology for the high-power (285 We) general-purpose heat source RTG (GPHS-RTG), shown in Figure 20, which is to provide power for NASA's Galileo spacecraft and the European Space Agency's Ulysses spacecraft.[21]

Table 2 illustrates the trends in RTG technology from SNAP-3B to GPHS-RTG, showing the overall steady progress to date.[2]

REACTOR POWER SOURCES

By the early 1950s it was apparent that nuclear reactors offered the potential to power some of the space satellite concepts then being considered. By the mid 1950s the U. S. had developed the basic design of a compact space reactor with hydrided zirconium-uranium alloy fuel elements coupled with liquid metal coolant for efficient heat transfer. The SNAP-2, SNAP-8 and SNAP-10A reactor power sources were developed from this basic design.[1,22,23,24] Table 3 lists the major U. S. space reactor programs, including both power and propulsion.[23,24]

SNAP-10A, which was the first and so far only space reactor flown by the U. S., evolved from the SNAP-2 sodium-potassium (NaK)-cooled Rankine converter reactor and the SNAP-10 conduction-cooled thermoelectric converter reactor. In 1960, the U. S. Air Force (USAF) and the U. S. Atomic Energy Commission (AEC) initiated the Space System Abbreviated Development Plan for Nuclear Auxiliary Power Orbital Test (SNAPSHOT) Program. Under the program, the USAF was to furnish the launch and satellite vehicles and the AEC was to furnish the SNAP-10A reactor units. The reactor was to provide not less than 500 We with a one-year operating lifetime.[22]

Included among the objectives of the SNAP-10A/SNAPSHOT program were to

- Demonstrate, proof test, and flight qualify SNAP-10A for subsequent operational use;
- Demonstrate the adequacy and safety of ground handling and launch procedures; and
- Demonstrate the adequacy and safety of automatic reactor startup in orbit.

As shown in Figure 21, the completed SNAP-10A system had the shape of a truncated cone with an overall length of 3.48 m and a mounting base diameter of 1.27 m. This configuration was dictated by minimum mass shield requirements, especially the requirement to eliminate neutron scattering around the steel-reinforced lithium hydride shadow shield. The base diameter was established by the Agena vehicle payload and the upper diameter was determined by the effective area of the reactor. The length was determined by the total radiator area requirement. The total system mass of the final flight unit (known as FS-4) was 435 kg including the shield.[22] The reactor is shown in Figure 22.

The power conversion system basically consisted of 2,880 SiGe thermoelectric elements mounted in groups of 72 along 40 stainless steel tubes through which the NaK coolant flowed. Figure 23 shows the overall thermodynamic cycle including a thermoelectric module. Despite its lower figure of merit at the SNAP-10A operating temperatures SiGe was chosen over PbTe because of (1) its stability to higher temperatures; (2) its potential for future performance growth; (3) its ease of manufacture;

and (4) its mechanical properties. The converter hot side operating temperature was about 780 K and the mean radiator temperature was about 610 K.[22]

On 3 April 1965, SNAP-10A was placed into a 1288 km by 1307 km orbit by an Atlas/Agena launch vehicle. Once it was confirmed that SNAP-10A was in a very long-lived orbit, the AEC authorized startup of the reactor.[22] Figure 24 is an artist's concept of SNAP-10A in space with the Agena.

The automatic startup of SNAP-10A was accomplished flawlessly. The response of the FS-4 flight system was in excellent agreement with predictions based on analog computer studies and ground test results obtained from the FS-3 reactor. Net power output ranged from a transient high of 650 We in the early part of the mission to a low of 527 We in the Sun after 43 days. The overall system efficiency was about 1.3%. In general, the system operated exactly as intended.[22]

On 16 May 1965, after 43 days of successful operation, the reactor was shut down by a spurious command caused by a failure of a voltage regulator on the Agena unregulated bus. There was no evidence of any malfunction in the SNAP-10A system. The FS-3 ground test twin to FS-4 successfully operated at full power for 10,000 hours thereby demonstrating the capability of SNAP-10A to operate unattended for a year.[22]

The SNAP-10A reactor successfully completed most of its objectives, including the following significant achievements:[22]

- First application of a nuclear reactor in space;
- First development of a reactor thermoelectric power system and the first use of such a system in space;
- First remote automatic startup of a nuclear reactor in space;

- First application of a high-temperature (810 K) liquid metal transfer system in space and the first application of a high-temperature spacecraft in space;
- First use of a nuclear shadow shield in space;
- Development and application of the highest powered thermoelectric power system to that time and the first use of a thermoelectric power system of that size in space; and
- First thermoelectric powered liquid metal pump and the first use of such a pump in space.

SPACE NUCLEAR SAFETY

From the beginning, the U. S. space nuclear power program has placed great emphasis on the safety of people and the protection of the environment. For RTGs, the safety philosophy is to contain or immobilize the radioisotope fuel to the maximum extent possible during all mission phases and postulated credible accidents. In the case of space nuclear reactor power systems, the current safety philosophy includes the launch of a nonoperating system so there is no buildup of radioactive fission products.[25]

The earlier NPS through SNAP-9A were designed to contain the fuel if the mission were aborted on the launch pad or during early ascent but to permit complete burnup of the fuel in the stratosphere. Worldwide dispersion and dilution of fine nuclear fuel particles would preclude local contamination. Transit 5BN-3, with a SNAP-9A power source, was launched on 21 April 1964 but failed to achieve orbit because of computer problems that affected the operation of the launch vehicle. The satellite reentered the atmosphere over the ocean east of Africa. The RTG burned up on reentry, as it was designed to do. The burnup of SNAP-9A added only about 4% to the total amount of plutonium in the environment. Subsequent studies by Italy, Japan, the U. K., and the U. S. have shown no measurable health effects from this reentry.[25,26,27,28,29,30]

All U. S. RTGs following SNAP-9A were designed to contain or immobilize the fuel through all credible accident conditions, including reentry and impact on Earth. The implementation of the new reentry philosophy was verified in two subsequent reentries:

- Abort of the launch of the Nimbus-B1 satellite on 18 May 1968 by the range safety officer because of a guidance error. The two SNAP-19B RTGs were recovered intact as designed.
- Damage of the Apollo 13 spacecraft from an oxygen tank explosion after a successful launch on 11 April 1970 leading to the intact reentry (as designed) of the SNAP-27 fuel cask over the South Pacific Ocean on 17 April 1970.

The U. S. Government employs an independent, formal multi-agency safety and environmental review of all NPS designs before the first launch. This process is illustrated in Figure 25. The overall U. S. approach is consistent with a U. N. working group report.[31,32] In fact, the U. S. has been an active participant in U. N. discussions on the safe use of NPS in outer space.[33]

The U. S. has supported the conclusion reached by the U. N. technical experts:

> "The Working Group reaffirmed its previous conclusion that NPS can be used safely in outer space, provided that all necessary safety requirements are met."[31]

CONCLUSION

Space nuclear power sources have proved to be reliable, long-lived sources of electrical power that have enabled the conduct of a number of important U. S. space missions, including the first long-term study of the surfaces of the Moon and Mars and the first exploratory visits to Jupiter, Saturn, and Uranus. In general, the NPS, from SNAP-3B to the MHW-RTG, met or exceeded their design requirements by providing power at or above that required and beyond the planned lifetime. All of the power sources met their safety requirements. This successful performance has laid a secure foundation for future U. S. missions that will use nuclear power.

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TABLE 1

SUMMARY OF SPACE NUCLEAR POWER SYSTEMS LAUNCHED BY THE UNITED STATES

POWER SOURCE[1]	SPACECRAFT	MISSION TYPE	LAUNCH DATE	STATUS
SNAP-3B7	TRANSIT 4A	NAVIGATIONAL	29 JUNE 1961	RTG OPERATED FOR 15 YEARS. SATELLITE NOW SHUTDOWN BUT OPERATIONAL
SNAP-3B8	TRANSIT 4B	NAVIGATIONAL	15 NOV. 1961	RTG OPERATED FOR 9 YEARS. SATELLITE OPERATION WAS INTERMITTENT AFTER 1962 HIGH-ALTITUDE NUCLEAR TEST. LAST REPORTED SIGNAL IN 1971
SNAP-9A	TRANSIT 5-BN-1	NAVIGATIONAL	28 SEPT. 1963	RTG OPERATED AS PLANNED. NON-RTG ELECTRICAL PROBLEMS ON SATELLITE CAUSED SATELLITE TO FAIL AFTER 9 MONTHS
SNAP-9A	TRANSIT 5-BN-2	NAVIGATIONAL	5 DEC. 1963	RTG OPERATED FOR OVER 6 YEARS. SATELLITE LOST NAVIGATIONAL CAPABILITY AFTER 1.5 YEARS
SNAP-9A	TRANSIT 5-BN-3	NAVIGATIONAL	21 APRIL 1964	RTG OPERATED AS PLANNED. MISSION WAS ABORTED BECAUSE OF LAUNCH VEHICLE FAILURE
SNAP-10A (REACTOR)	SNAPSHOT	EXPERIMENTAL	3 APRIL 1965	REACTOR OPERATED SUCCESSFULLY AS PLANNED. SATELLITE SHUTDOWN REACTOR AFTER 43 DAYS
SNAP-19B2	NIMBUS-B-1	METEOROLOGICAL	18 MAY 1968	RTGs OPERATED AS PLANNED. MISSION WAS ABORTED BECAUSE OF RANGE SAFETY DESTRUCT. RTGs RECOVERED
SNAP-19B3	NUMBUS III	METEOROLOGICAL	14 APRIL 1969	RTGs OPERATED FOR OVER 2.5 YEARS (NO DATA TAKEN AFTER THAT)
SNAP-27	APOLLO 12	LUNAR	14 NOV. 1969	RTG OPERATED FOR ABOUT 8 YEARS (UNTIL STATION WAS SHUTDOWN)
SNAP-27	APOLLO 13	LUNAR	11 APRIL 1970	MISSION ABORTED ON WAY TO MOON. HEAT SOURCE RETURNED TO SOUTH PACIFIC OCEAN
SNAP-27	APOLLO 14	LUNAR	31 JAN. 1971	RTG OPERATED FOR ABOUT 6.5 YEARS (UNTIL STATION WAS SHUTDOWN)
SNAP-27	APOLLO 15	LUNAR	26 JULY 1971	RTG OPERATED FOR OVER 6 YEARS (UNTIL STATION WAS SHUTDOWN)
SNAP-19	PIONEER 10	PLANETARY	2 MAR. 1972	RTGs STILL OPERATING. SPACECRAFT SUCCESSFULLY OPERATED TO JUPITER AND IS NOW BEYOND ORBIT OF PLUTO
SNAP-27	APOLLO 16	LUNAR	16 APRIL 1972	RTG OPERATED FOR ABOUT 5.5 YEARS (UNTIL STATION WAS SHUTDOWN)
TRANSIT-RTG	"TRANSIT" (TRIAD-01-1X)	NAVIGATIONAL	2 SEPT 1972	RTG STILL OPERATING
SNAP-27	APOLLO 17	LUNAR	7 DEC. 1972	RTG OPERATED FOR ALMOST 5 YEARS (UNTIL STATION WAS SHUTDOWN)
SNAP-19	PIONEER 11	PLANETARY	5 APRIL 1973	RTGs STILL OPERATING. SPACECRAFT SUCCESSFULLY OPERATED TO JUPITER, SATURN, AND BEYOND
SNAP-19	VIKING 1	MARS	20 AUG. 1975	RTGs OPERATED FOR OVER 6 YEARS (UNTIL LANDER WAS SHUTDOWN)
SNAP-19	VIKING 2	MARS	9 SEPT. 1975	RTGs OPERATED FOR OVER 4 YEARS UNTIL RELAY LINK WAS LOST
MHW-RTG	LES 8	COMMUNICATIONS	14 MAR. 1976	RTGs STILL OPERATING
MHW-RTG	LES 9	COMMUNICATIONS	14 MAR. 1976	RTGs STILL OPERATING
MHW-RTG	VOYAGER 2	PLANETARY	20 AUG. 1977	RTGs STILL OPERATING. SPACECRAFT SUCCESSFULLY OPERATED TO JUPITER, SATURN, URANUS, AND BEYOND
MHW-RTG	VOYAGER 1	PLANETARY	5 SEPT. 1977	RTGs STILL OPERATING. SPACECRAFT SUCCESSFULLY OPERATED TO JUPITER, SATURN, AND BEYOND

[1] SNAP STANDS FOR SYSTEMS FOR NUCLEAR AUXILIARY POWER. ALL ODD-NUMBERED SNAP POWER PLANTS USE RADIOISOTOPE FUEL. EVEN-NUMBERED SNAP POWER PLANTS HAVE NUCLEAR FISSION REACTORS AS A SOURCE OF HEAT. MHW-RTG STANDS FOR THE MULTIHUNDRED WATT RADIOISOTOPE THERMOELECTRIC GENERATOR.

TABLE 2. TRENDS IN RTG TECHNOLOGY

PARAMETER	SNAP-3B	SNAP-9A	SNAP-27	TRANSIT-RTG	SNAP-19	MHW-RTG	GPHS-RTG
MISSION	TRANSIT 4	TRANSIT 5BN	APOLLO	TRIAD	PIONEER	VOYAGER	GALILEO/ULYSSES
BOM POWER PER RTG, We	2.7	26.8	73.4	35.6	40.3	158.0	300[a]
THERMOELECTRIC MATERIAL	PbTe 2N/2P	PbTe 2N/2P	PbTe 3N/3P	PbTe 2N/3P	PbTe 2N/ TAGS-85	SiGe	SiGe
Pu-238 FUEL FORM	Metal	Metal	Oxide (Microspheres)	PMC[b]	PMC[b]	Pressed Oxide	Pressed Oxide
CONVERSION EFFICIENCY, %	5.1	5.1	5.0	4.2	6.2	6.6	6.8
SPECIFIC POWER, We/kg	1.29	2.2	2.3[c]	2.6	3.0	4.2	5.3

[a]Approximate power for originally planned 1986 launches (see Reference 21)
[b]Plutonia Molybdenum Cermet
[c]The SNAP-27 specific power is shown with the fuel-cask mass included.

TABLE 3
PRINCIPAL U. S. SPACE NUCLEAR REACTOR PROGRAMS

Power Plant	Purpose	Power Level	Operating Temp (K)	Period	Type Reactor	Fuel	Converter	Development Level
Rover (includes NERVA)	Propulsion	365-500MW$_t$	2,450	1955–1973	Epithermal	UC		Twenty reactors tested. Demonstrated all components of flight engine >2 hr. Ready for flight engine development.
Fluidized Bed Reactor	Propulsion	1000 MW$_t$	3,000	1958–1973	Thermal	UC-ZrC		Cold flow, bed dynamics experiments successful.
Gaseous Core Reactors	Propulsion and Electricity	4600 MW$_t$	10,000 1,500	1959–1978	Fast	Uranium plasma UF_6	Brayton	Successful critical assembly of UF_6.
SNAP-2	Electricity	3 kW$_e$	920	1957–1963	Thermal	Uranium zirconium hydride	Mercury Rankine	Development level. Tested two reactors with longest test reactor operated 10,500 hrs. Precursor for SNAP-8 and —10A.
SNAP-10A	Electricity	0.5 kW$_e$	810	1960–1966	Thermal	Uranium zirconium hydride	Thermoelectric	Flight tested reactor 43 days. Tested reactor with thermoelectrics in 417-day ground test.
SNAP-8	Electricity	30-60 kW$_e$	975	1960–1970	Thermal	Uranium zirconium hydride	Mercury Rankine	Tested two reactors. Demonstrated 1 yr operation. Non-nuclear components operated 10,000 hr and breadboard 8,700 hr.
Advanced Hydride Reactors	Electricity	5 kW$_e$	920	1970–1973	Thermal	Uranium zirconium hydride	Thermoelectric and Brayton	PbTe thermoelectrics tested to 42,000 hrs.
SNAP-50	Electricity	300-1200 kW$_e$	1,365	1962–1965	Fast	UN, UC	Potassium Rankine	Fuels tested to 6,000 hr.
Advanced Metal-Cooled Reactor	Electricity	300 kW$_e$	1,480	1965–1973	Fast	Uranium nitride	Brayton and potassium Rankine	Non-nuclear potassium Rankine cycle components demonstrated to 10,000 hr. Ready for breadboard loop.
710 Gas Reactor	Electricity and propulsion	200 kW$_e$	1,445	1962–1968	Fast	UO_2	Brayton	Fuel element tested to 7,000 hr.
In-Core Thermionic Reactor	Electricity	5-250 kW$_e$	2,000	1959–1973	Fast or thermal driver	UO_2, UC-ZrC	In-core thermionics	Integral fuel element, thermionic diode demonstrated >1 yr operation.
Nuclear Electric Propulsion	Electricity	400 kW$_e$	1,675	1974–1981	Fast	UO_2	Out-of-core thermionics	Limited testing on thermionic elements.
SPAR/SP-100	Electricity	100 kW$_e$	1,500	1979–present	Fast	UN	Thermoelectric	Limited testing on core heat pipes and advanced thermoelectric materials

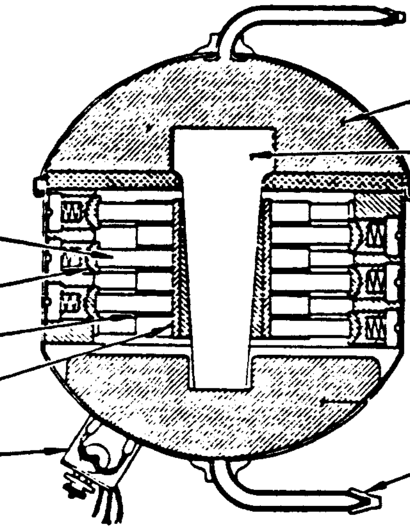

Figure 1. Schematic of the SNAP-3B RTG. The overall dimensions were 12.1 cm in diameter by 14 cm high.

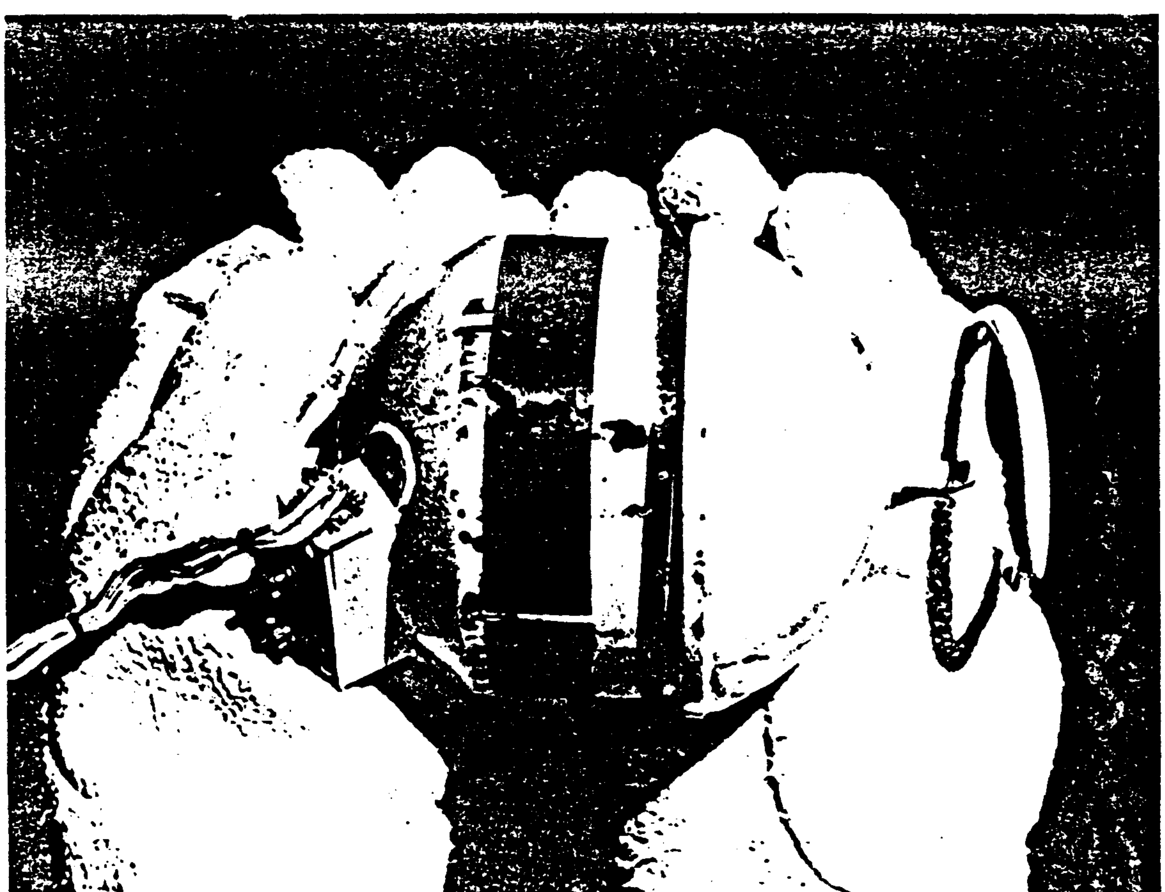

Figure 2. Photograph of a SNAP-3B RTG

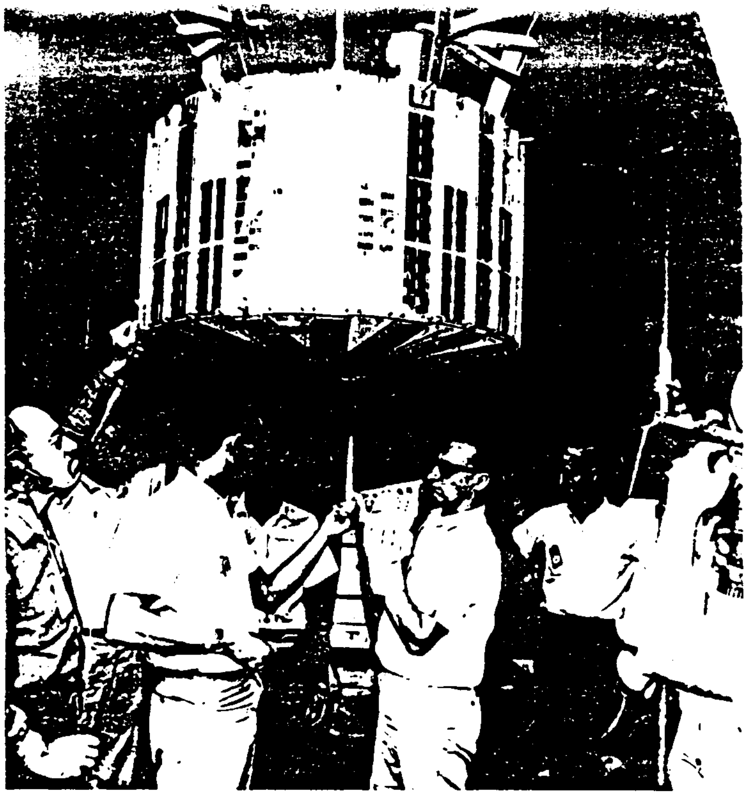

Figure 3. Photograph of Paul J. Dick of Teledyne Energy Systems installing a SNAP-3B RTG on the Transit 4A satellite in June 1961. This was the first flight of an NPS.

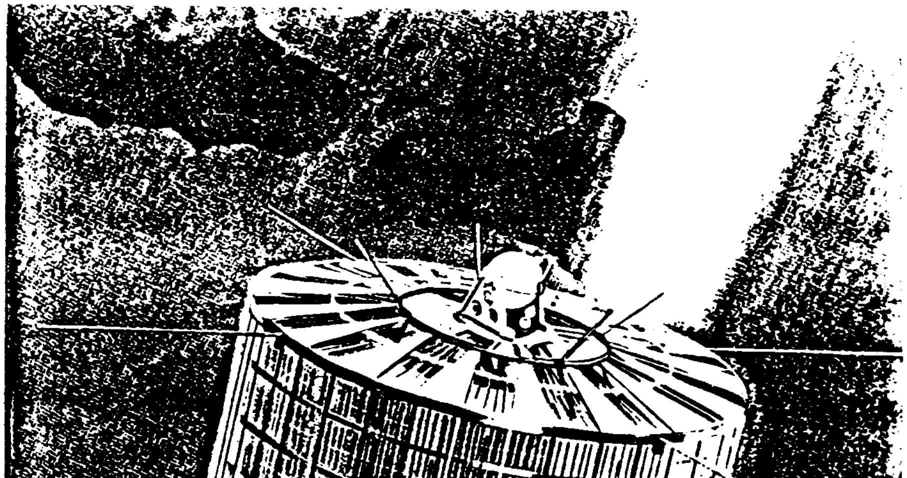

Figure 4. Artist's conception of the Transit 4A satellite in orbit showing the SNAP-3B RTG mounted on one end.

SNAP-9A RTG

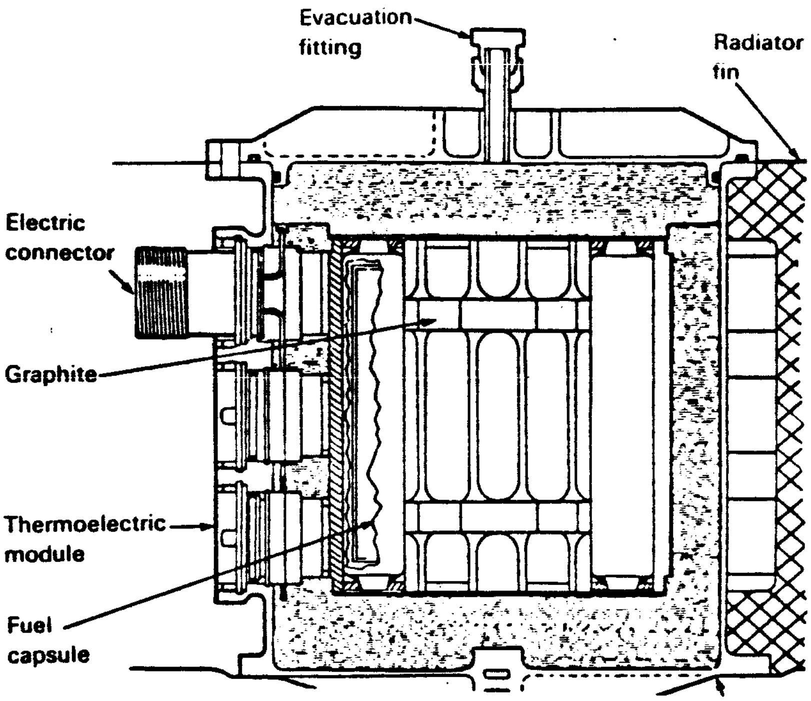

Figure 5. **Schematic of the SNAP-9A RTG. The main body of the generator was a cylindrical magnesium-thorium shell 22.9 cm in diameter and 21.3 cm high.**

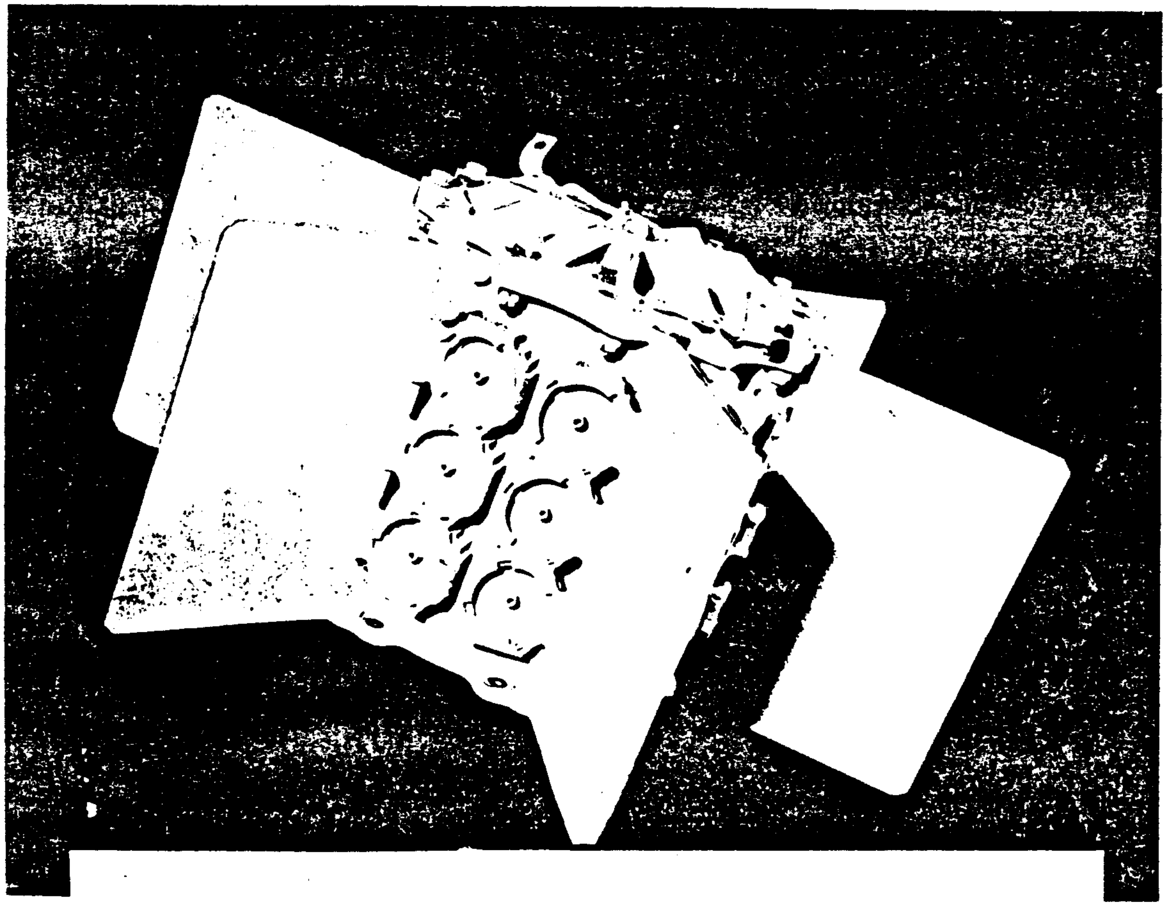

Figure 6. **Photograph of a SNAP-9A RTG.**

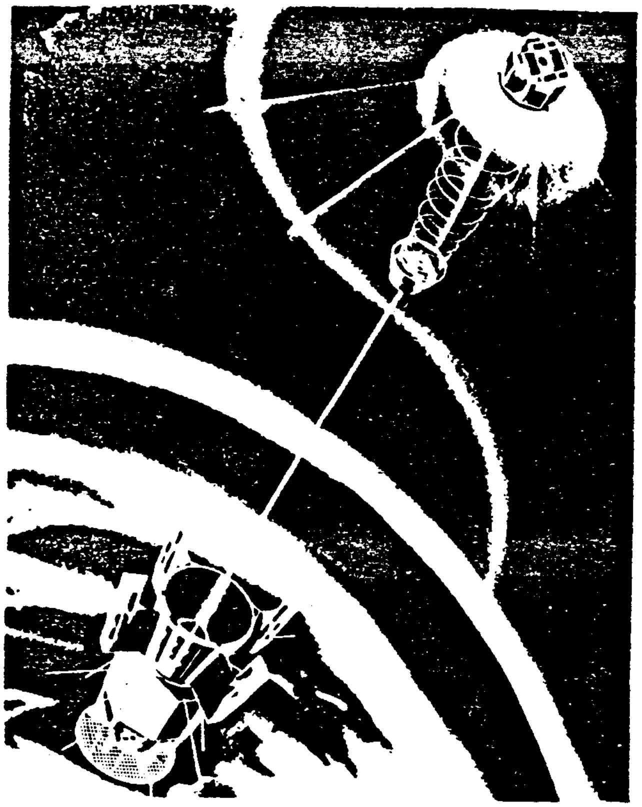

Figure 7. Artist's conception of the Transit 5BN-1 satellite in orbit. The SNAP-9A RTG is at the aft end.

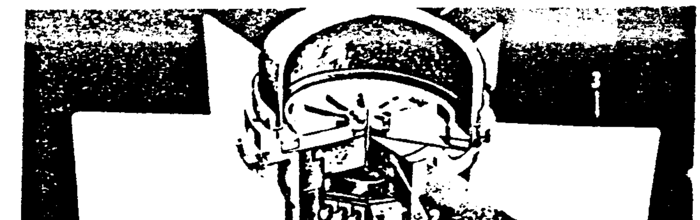

Figure 8. Schematic of the Viking/SNAP-19 RTG. The height is 40.4 cm and the fin span is 58.7 cm. The three SNAP-19 RTG concepts shared a common technology heritage.

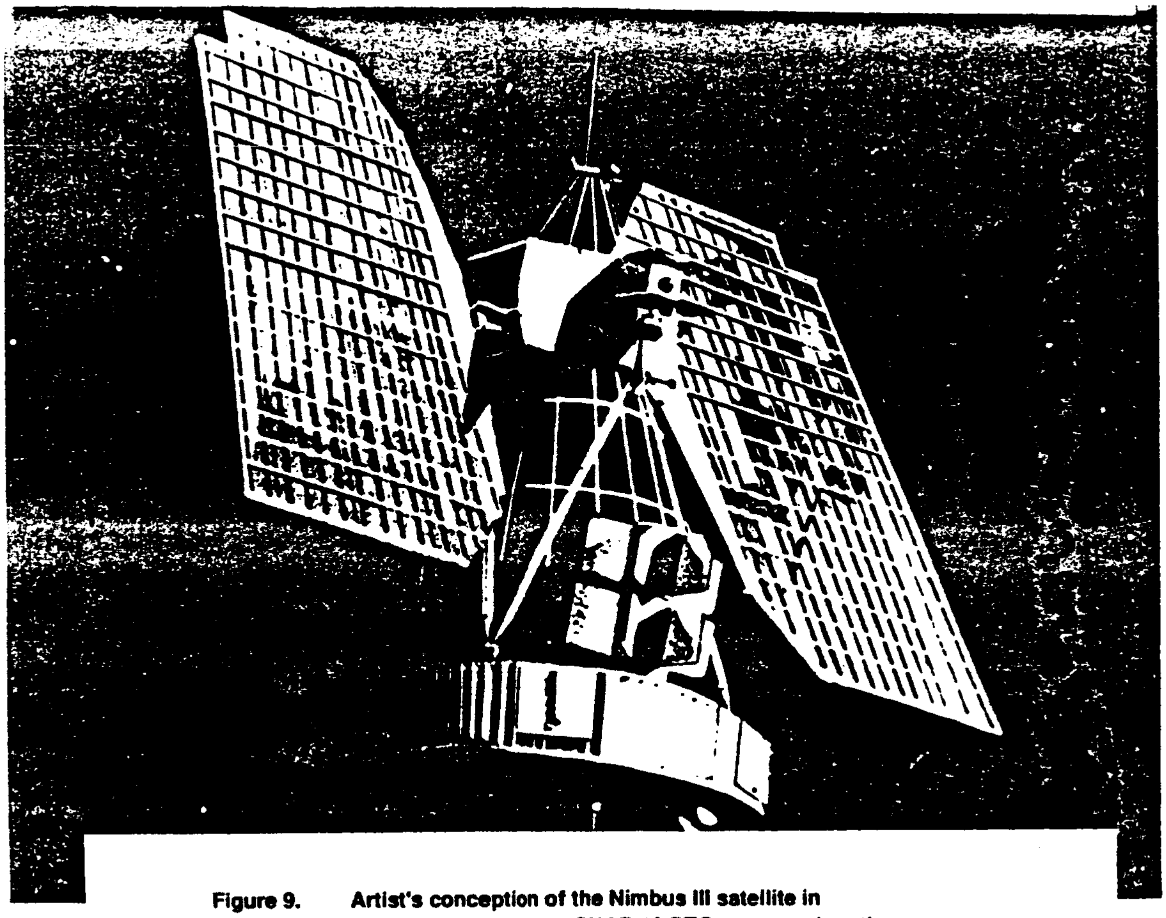

Figure 9. Artist's conception of the Nimbus III satellite in orbit showing the two SNAP-19 RTGs mounted on the base platform.

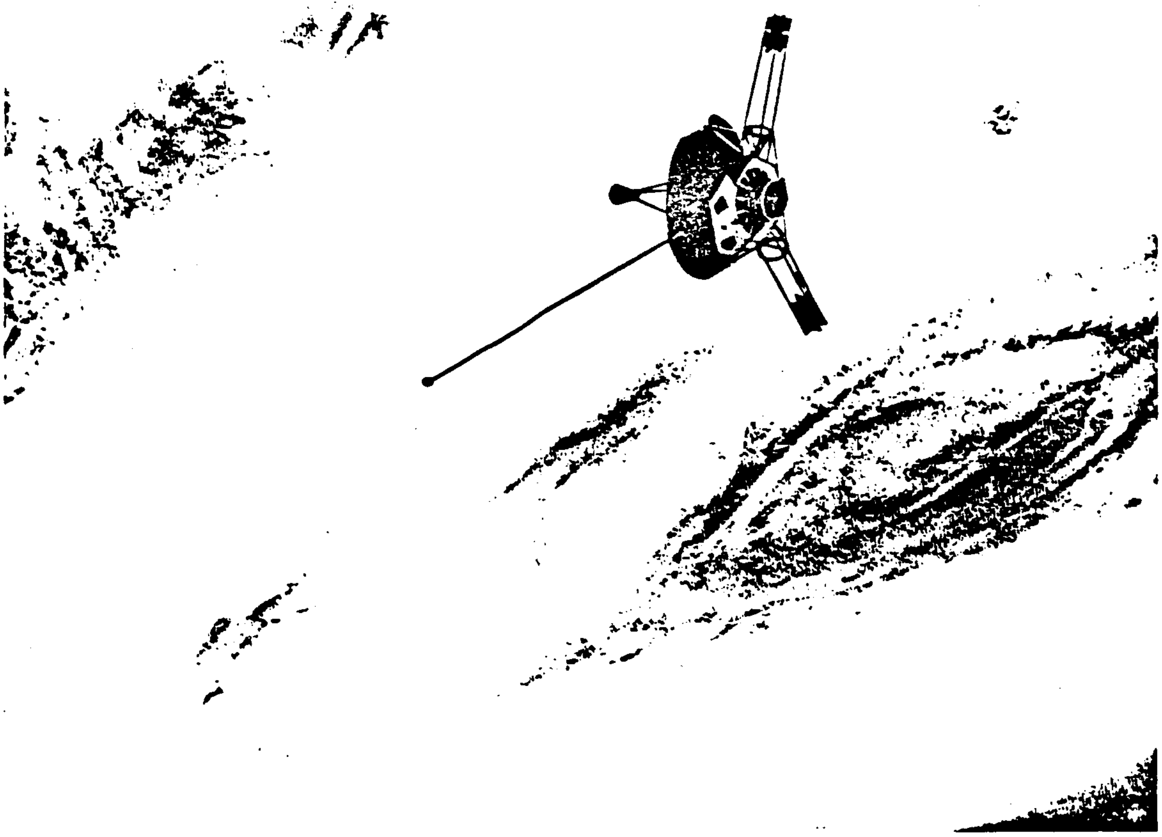

Figure 10. Artist's conception of the Pioneer 10 spacecraft flying past Jupiter. The four SNAP-19 RTGs are

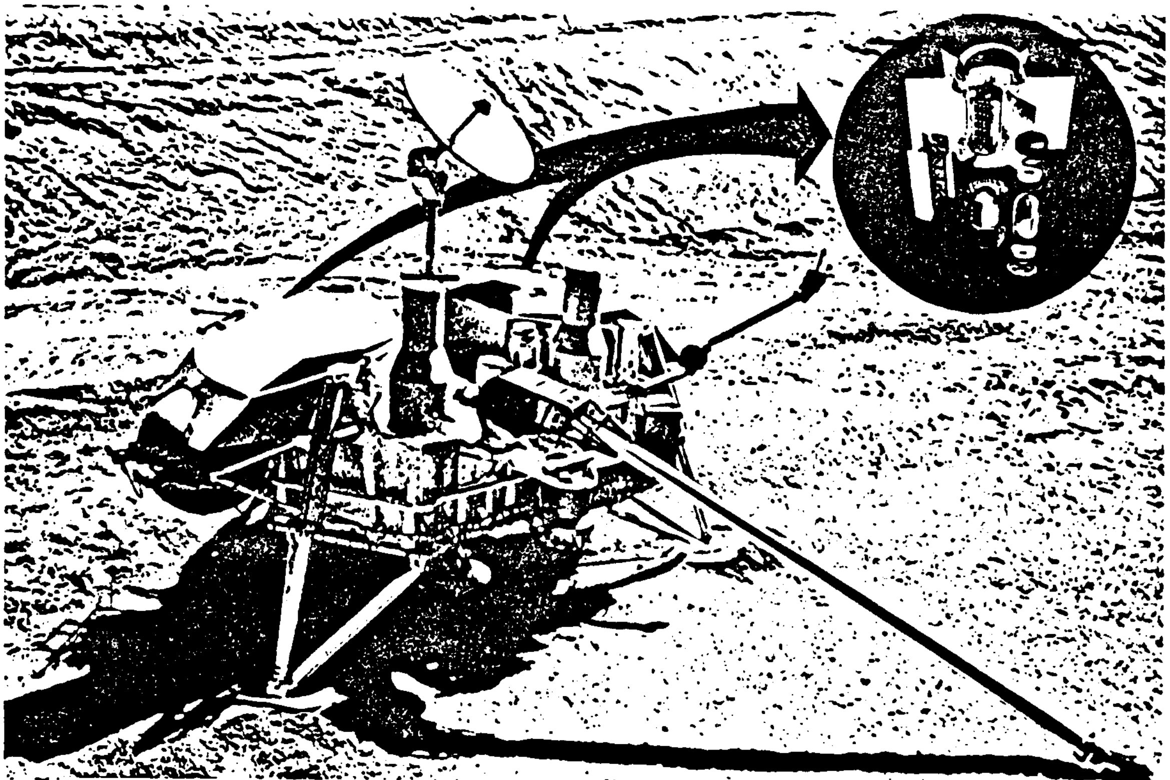

Figure 11. Engineering mockup of the Viking Lander with the location of the two SNAP-19 RTGs indicated.

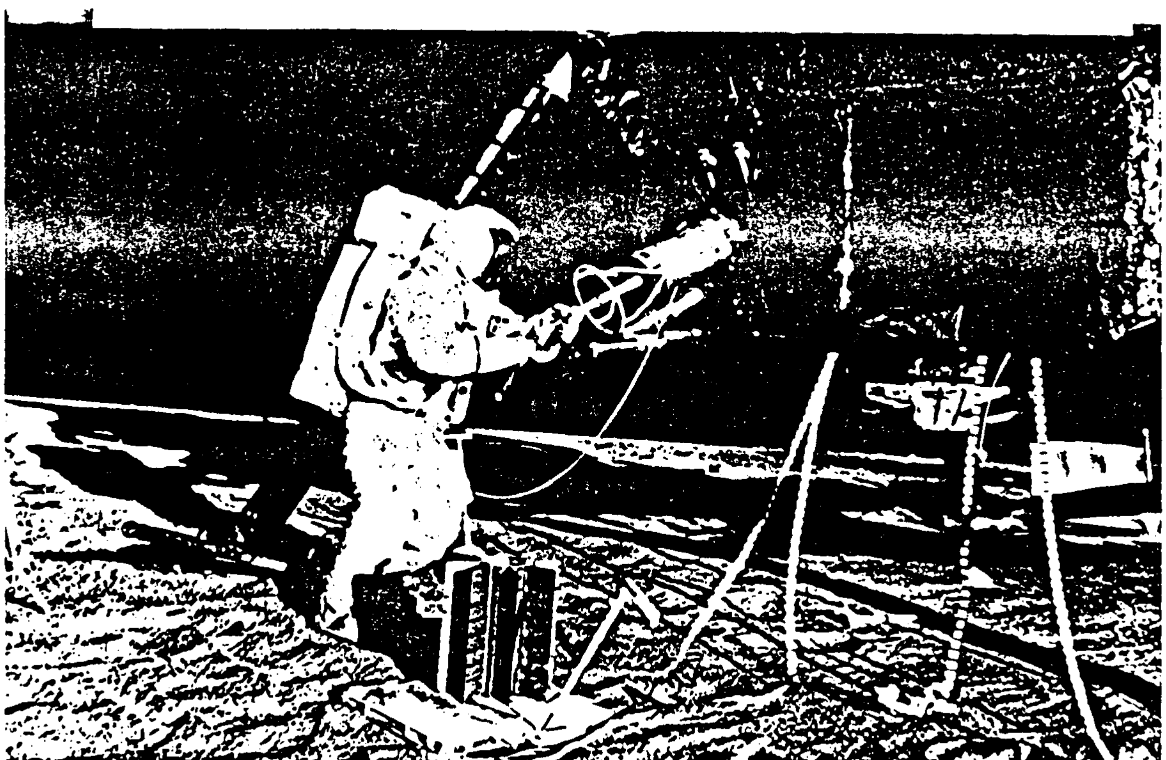

Figure 12. Astronaut Alan L. Bean is shown removing the SNAP-27 heat source in preparation for insertion into the converter shown in the foreground during the Apollo 12 mission in November 1969.

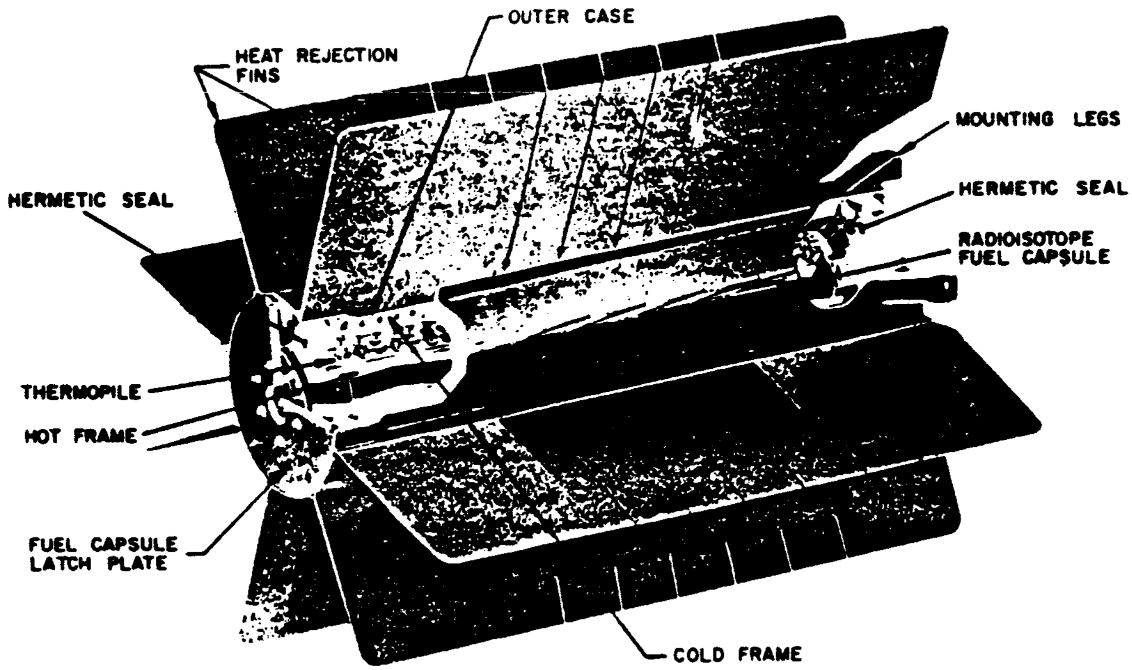

Figure 13. **Schematic of the SNAP-27 RTG. The overall dimensions were 46 cm high and 40.0 cm in diameter (including the fins).**

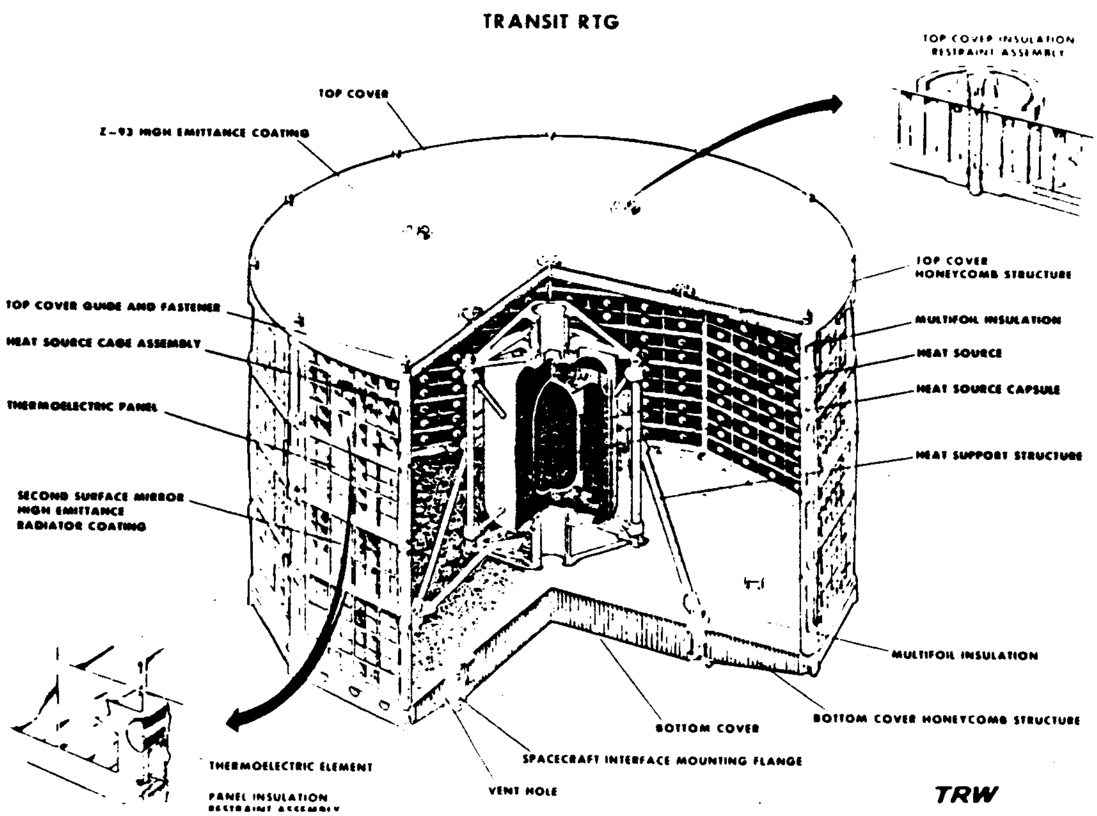

Figure 14. **Schematic of the TRANSIT RTG. The distance across flats is 61 cm and the panel height is 36.3 cm.**

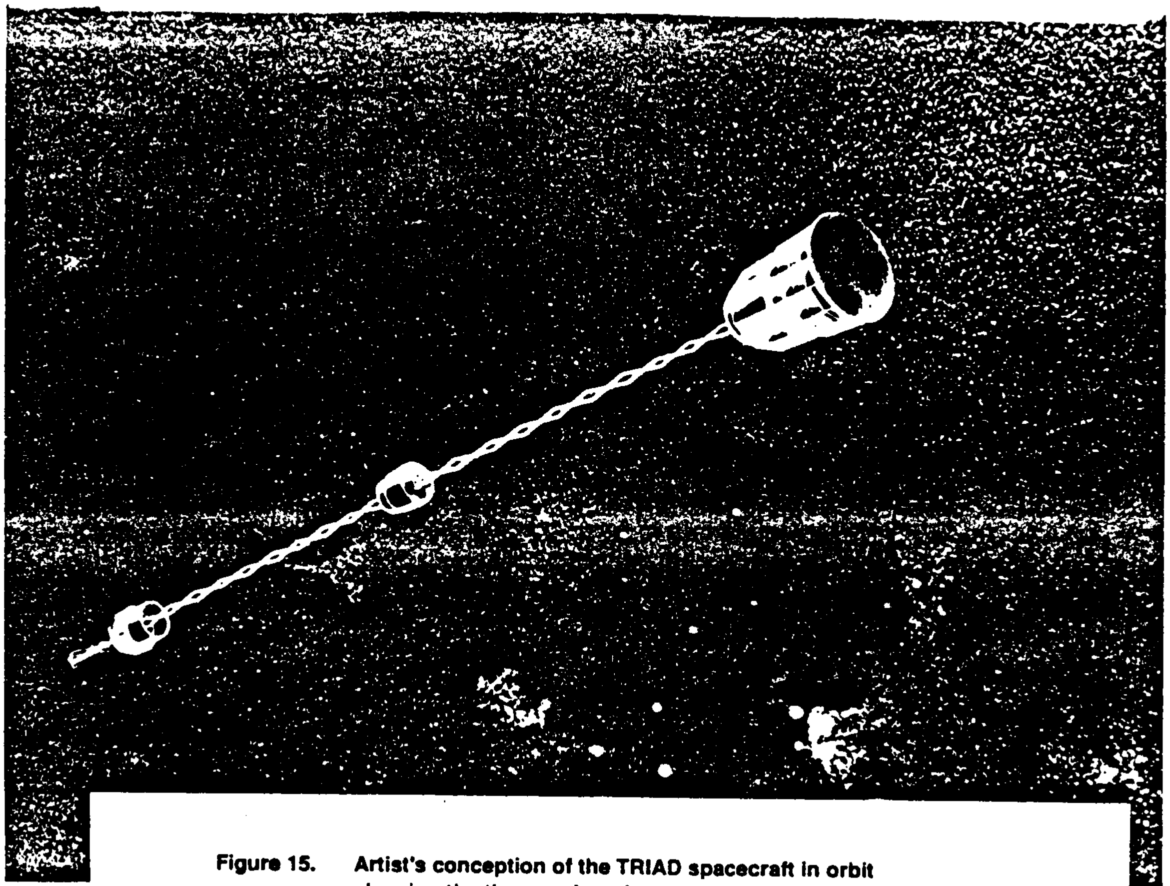

Figure 15. Artist's conception of the TRIAD spacecraft in orbit showing the three main units: power (in the upper right with the TRANSIT RTG), disturbance compensation system (in the middle), and main electronics (in the lower left).

MHW-RTG

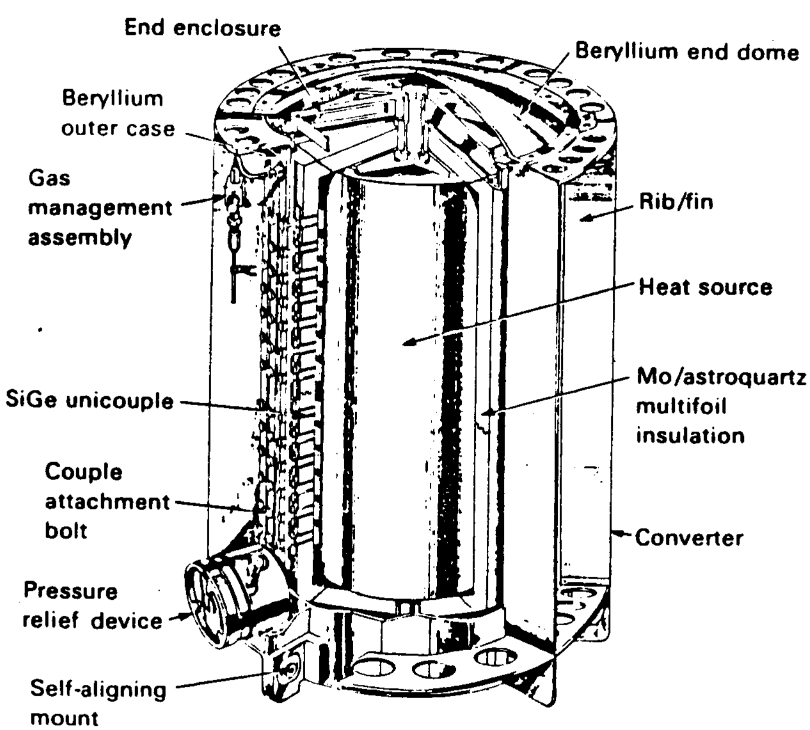

Figure 16. Schematic of the MHW-RTG. The overall diameter of the RTG is 39.73 cm and its length is 58.31 cm.

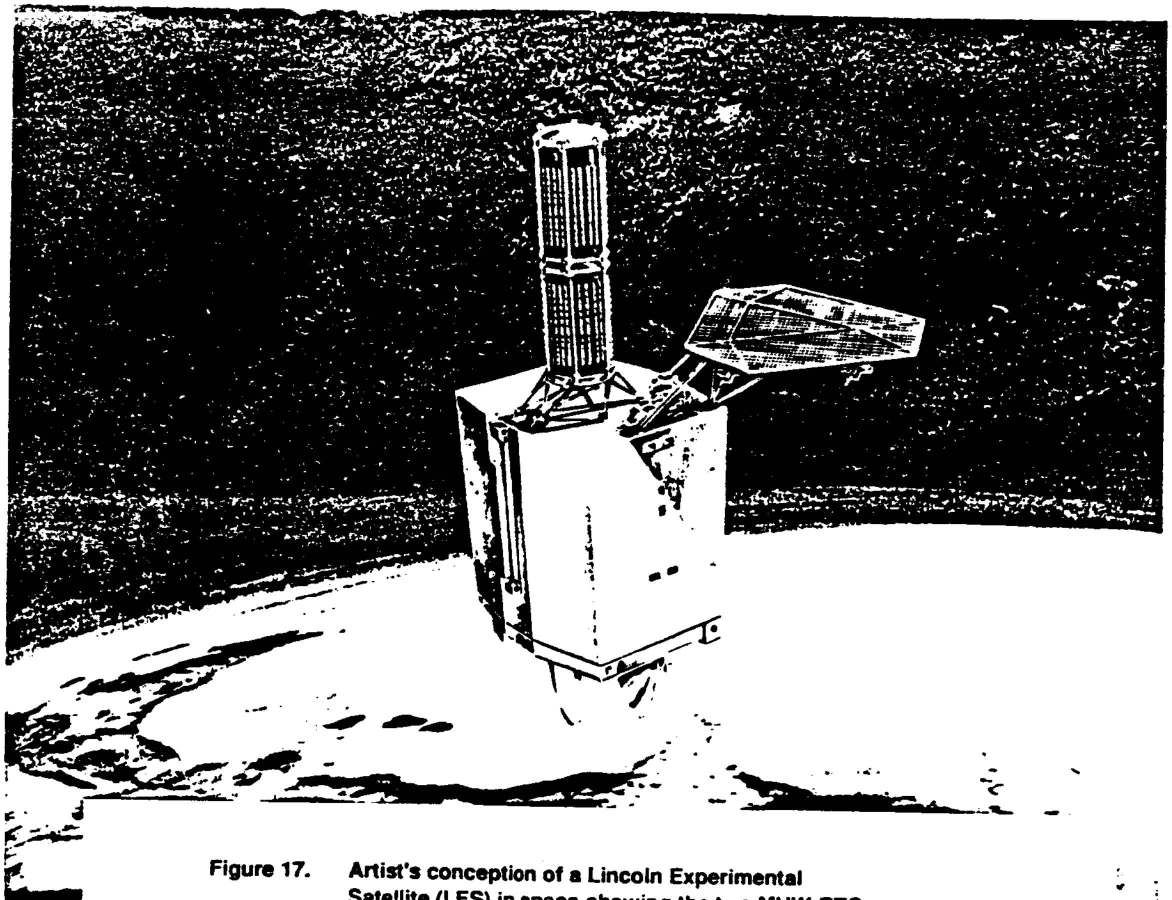

Figure 17. Artist's conception of a Lincoln Experimental Satellite (LES) in space showing the two MHW-RTGs mounted on one end.

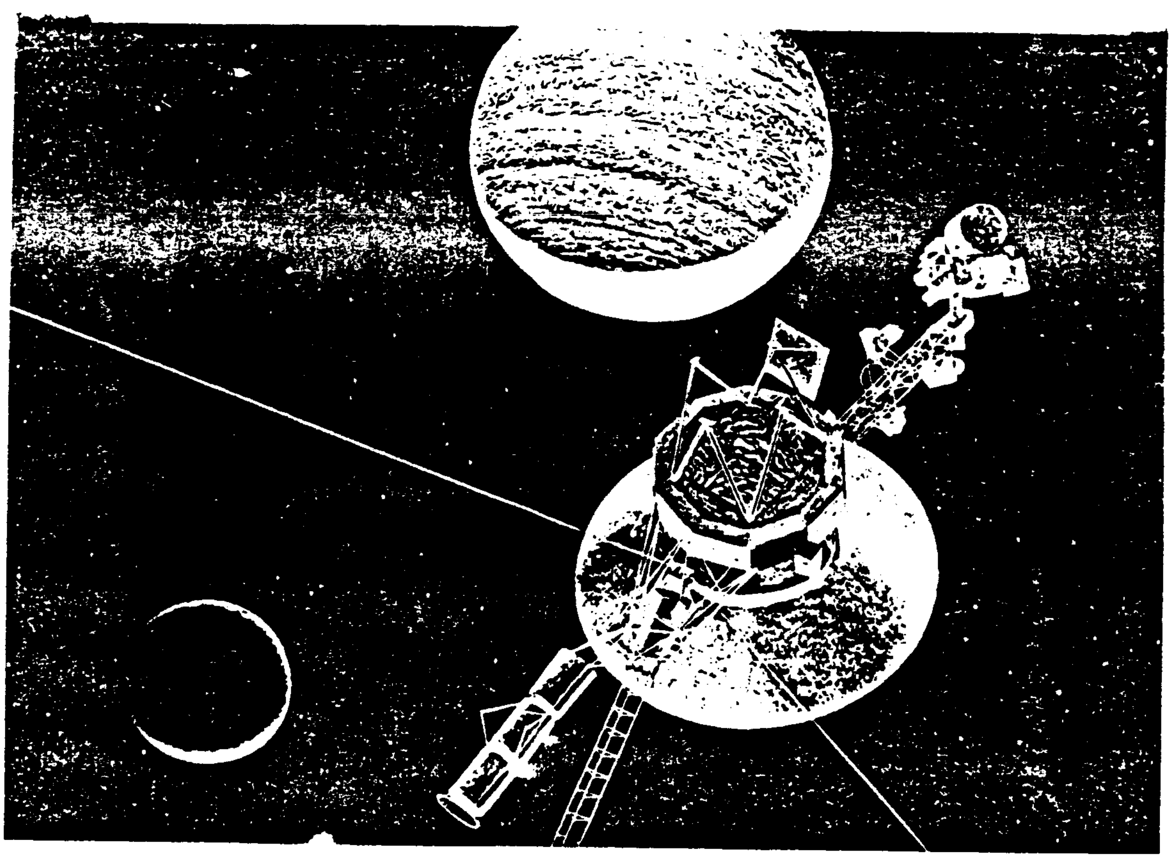

Figure 18. Artist's conception of the Voyager 2 spacecraft passing Neptune in August 1989 with Neptune's largest moon, Triton, shown in the lower left.

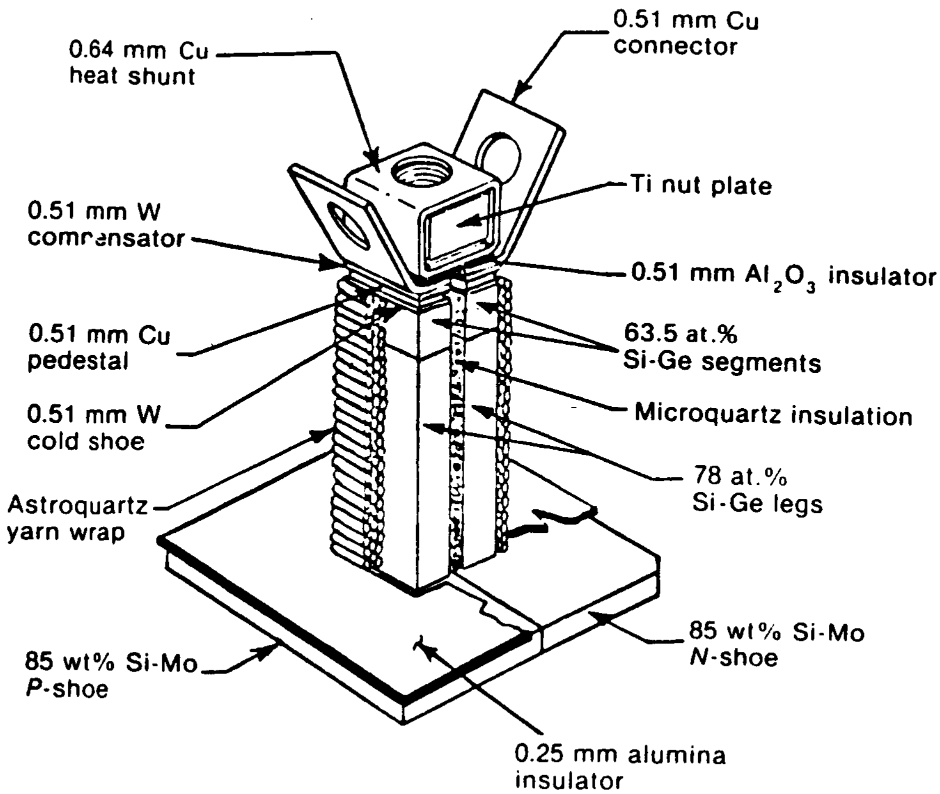

Figure 19. Cutaway of the silicon-germanium thermoelectric element ("unicouple") used in the MHW-RTGs and GPHS-RTGs. Each MHW-RTG has 312 unicouples. Each GPHS-RTG has 572 unicouples.

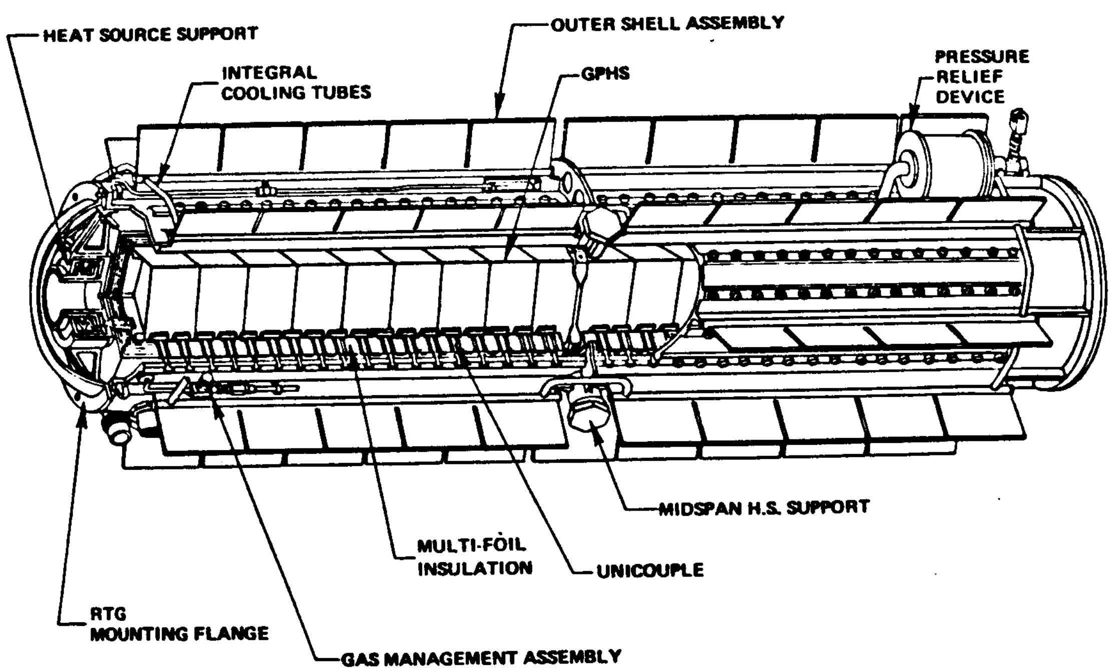

Figure 20. Cutaway of the General-Purpose Heat Source (GPHS) RTG which is to be used on the Galileo mission to Jupiter and the Ulysses mission to explore the polar regions of the Sun.

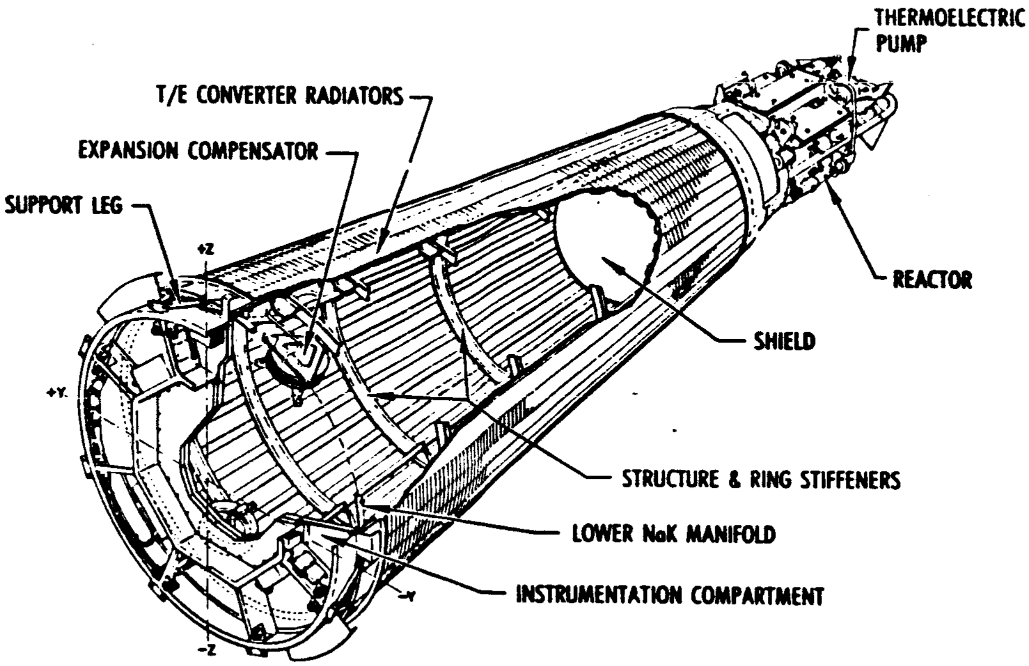

Figure 21. **Cutaway of the SNAP-10A reactor system. The term T/E stands for "thermoelectric".**

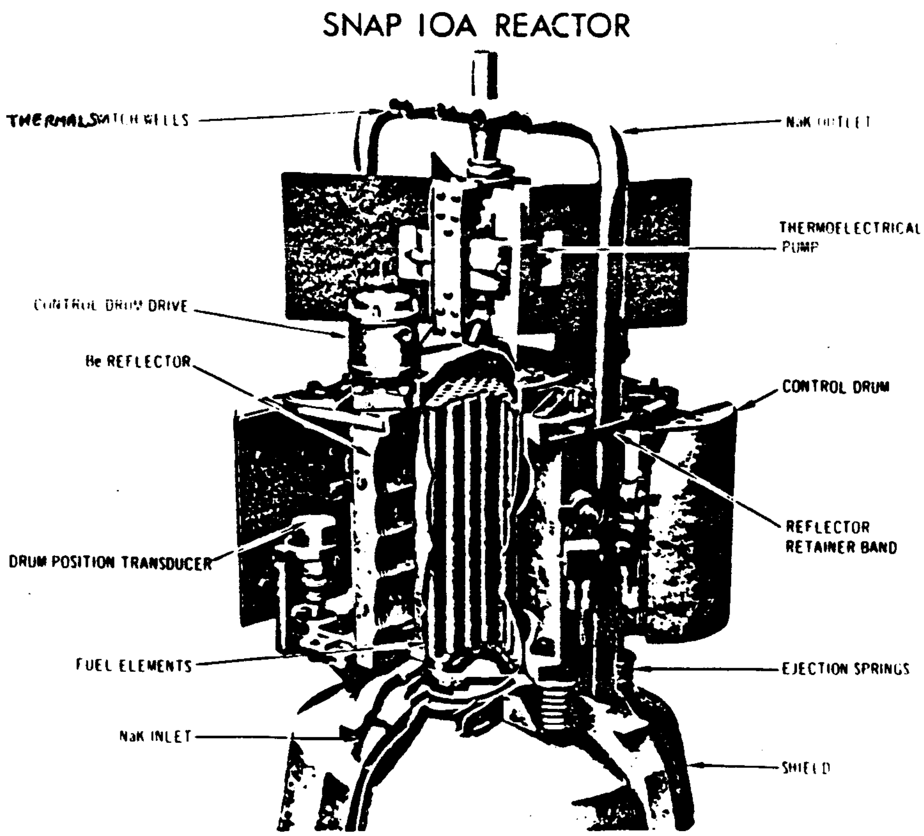

Figure 22. **Cutaway of the SNAP-10A reactor.**

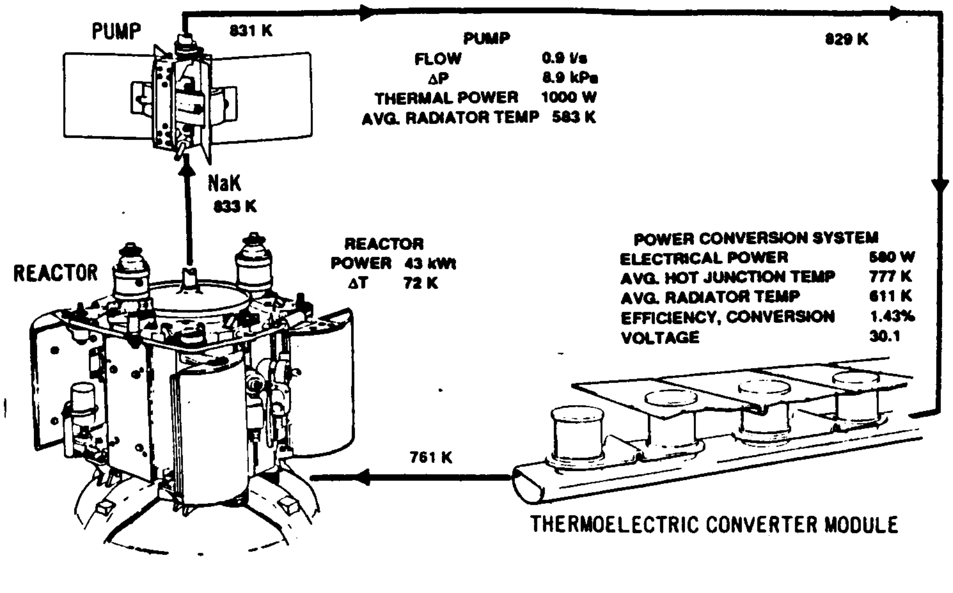

Figure 23. Schematic of the SNAP-10A thermodynamic cycle.

Figure 24. Artist's conception of the SNAP-10A reactor mounted on the Agena launch vehicle in space.

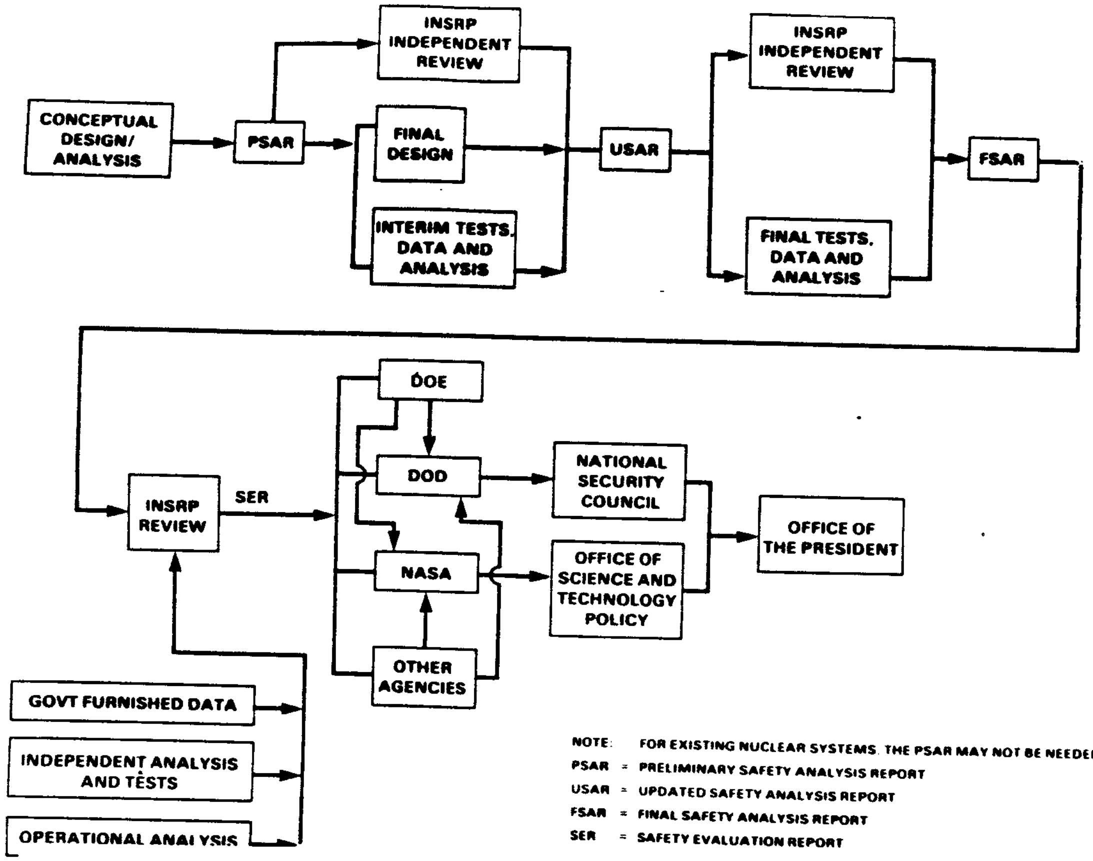

Figure 25. Diagram of the U. S. flight safety review process for space nuclear power sources.

AGENDA

JOINT MEETING ON POWER AND PROPULSION TECHNOLOGIES FOR CARGO VEHICLE PROPULSION

NASA HEADQUARTERS
FEDERAL BUILDING 6, ROOM 5092
400 MARYLAND AVENUE, SW, WASHINGTON, DC
8:30 AM TO 4:30 PM

WELCOME AND OPENING REMARKS General overview of meeting purpose, i.e., to exchange information and technology status on ongoing power and propulsion technologies relative to the Cargo Vehicle Propulsion work	G. L. Bennett, NASA J. F. Mondt, JPL J. W. Warren, DOE
OVERVIEW OF PATHFINDER AND CARGO VEHICLE PROPULSION General background on Pathfinder program with particular focus on the Cargo Vehicle Propulsion element, including what it is and what it is not.	J. Mankins, NASA
CARGO VEHICLE PROPULSION PROGRAM PLAN Review of the approved Cargo Vehicle Propulsion program plan and general discussion of program/project management.	J. R. Stone, NASA/LeRC
ELECTRIC PROPULSION TECHNOLOGY STATUS Brief status of technology on proposed Cargo Vehicle Propulsion electric propulsion systems,i.e., ion engines and MPD thrusters.	J. S. Sovey, NASA/LeRC D. Q. King, JPL
SPACE NUCLEAR POWER TECHNOLOGY STATUS Summary of technology status on SP-100 and Multi-Megawatt (MMW) space nuclear power programs, including schedules, projected availability, etc.	J. F. Mondt, JPL M. Stanley, INEL
WRAP-UP AND SUMMARY General summation of the meeting and review of actions/future plans/ need for additional meetings, etc.	G. L. Bennett, NASA

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LIST OF ATTENDEES

JOINT MEETING ON POWER AND PROPULSION TECHNOLOGIES FOR CARGO VEHICLE PROPULSION

8 February 1989

Name	Organization	Telephone
John Barnett	JPL	818-354-4037
Gary L. Bennett	NASA/RP	202-453-9111
Stanley K. Borowski	NASA/LeRC	216-433-8134
David Byers	NASA/LeRC	216-433-2447
John Dearien	INEL/MMW	208-526-9374
Darrell Jan	JPL	818-354-4542
David Q. King	JPL	818-354-3315
John C. Mankins	NASA/RS	202-453-3658
Lee Mason	NASA/LeRC	216-433-5394
Jack Mondt	JPL	818-354-1900
Thomas J. Pivirotto	JPL	818-354-3132
Greg Reck	NASA/RP	202-453-2847
A. Dan Schnyer	NASA/RP	202-453-2855
Jim Sovey	NASA/LeRC	216-433-2420
Marland Stanley	INEL/MMW	208-526-2041
Jim Stone	NASA/RP	202-453-9113
Jimmy M. Underwood	NASA/Z	202-453-8932
Earl VanLandingham	NASA/RP	202-453-2847
Earl Wahlquist	DOE/NE	301-353-3321
John Warren	DOE/NE	301-353-6491